Department of Health and Social Security

Hearing and Noise in Industry

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The studies described here comprise an investigation undertaken jointly by the Medical Research Council and the National Physical Laboratory, and commissioned in 1962 by the former Ministry of Pensions and National Insurance.

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Authorship of the Appendices

The overall scientific direction of the project devolved upon the two principal authors and for the way they approached and executed the task, as well as for the results and the conclusions drawn from them, they accept responsibility. But the scale of the investigation as well as its nature required the efforts of a team in which were necessarily represented diverse scientific disciplines.

The principal authors wish to place on record their indebtedness to their many collaborators and, in particular, to those who shared the task of preparing the technical appendices, namely:

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Foreword

by The Rt. Hon. Richard Crossman, CBE, MP

Secretary of State for Social Services

It gives me pleasure to introduce this work which reproduces with minor editorial amendments and the addition of a preface, a report made to me of the findings of a long-term research project into the nature of industrial noise and its effect on hearing. This research was commissioned under powers provided by the National Insurance (Industrial Injuries) Act, following a recommendation made by the Industrial Injuries Advisory Council.

The research has a bearing both on the question of prevention of hearing impairment in industry, and on the question of compensation for occupational hearing loss which is the concern of the Department of Health and Social Security through its responsibility for the scheme of industrial injuries benefits. Before a disease can be prescribed for the purposes of the Industrial Injuries Act, certain statutory conditions must be satisfied; briefly, the disease must represent a risk of employment rather than a general risk to the population as a whole, and it must be possible to establish the attribution to employment in individual cases. In both respects deafness presents very great difficulties, because it is a common condition, particularly among older people; and because it has many causes, more than one of which may contribute to the hearing loss sustained in a particular case.

The fundamental research undertaken by the team led by Professor W. Burns and Dr D. W. Robinson, designed as it was to throw light on the questions that need to be answered, was an essential preliminary to the detailed consideration of the possibility of prescription. But in a wider sense the research findings, as presented in their report, will I am sure provide a valuable work of reference for many years to come to all who are concerned with the problem of noise in industry.

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Preface

In the last century the industrial revolution brought in its train new conditions of work, and contact with new physical and chemical agents. Inevitably some of these, by painful experience, were found to be harmful to those exposed to them. Gradually these injurious factors were identified, and steps were taken by governments and by industry to control such hazards. As a corollary to this, legislation was enacted to compensate those persons who had suffered injury. More recently, perhaps over the last thirty years, there has been a noticeable increase in efforts to promote the concept of industrial health, and both industry and government have participated effectively in the pursuit of this objective.

Compared with the well-established control of many toxic agents and potentially harmful environments, which is enforced by legislation, and which in Britain provides for compensation under the Industrial Injuries Act, concern for the control of noise and its possible effects has become manifest somewhat later. This is not unexpected since, of the many potentially harmful accompaniments of modern technology, noise is perhaps one of the more difficult to control, both in its physical nature and because its effects are not easily distinguishable from other sources of hearing impairment. Furthermore, the effects of noise have not been known in detail despite appreciable efforts to elucidate them.

In most cases, the effects of exposure to noise in industry are not dramatic. The ill effects are mainly manifest as an insidious reduction in the acuity of hearing, clearly recognised by the person and by his family and friends only after some years of exposure to the noise. By this time, a significant disability, such as the inability to hear clearly normal conversational speech, may have become established. The control of occupational hearing loss is thus clearly desirable. This control would be directed towards the prevention of the condition, basically by noise reduction, which would be exercised

both at a general level, designed to protect whole groups of people and also, ideally, at an individual level, where the wide range of susceptibility of individuals to noise-induced hearing loss would be taken into account.

In keeping with the legislation covering other specific hazards to health which may occur in industry, a corollary would be that the case for designating occupational hearing loss as a compensable disability under the Industrial Injuries Act should be considered. For the purpose of examining the problems underlying the assessment of noise as an industrial hazard, particularly with regard to compensation, the Ministry of Pensions and National Insurance, in 1961, formally commissioned the research which is being reported here, the work being allocated jointly to the Medical Research Council and the National Physical Laboratory.

The situation at that time was that occupational hearing loss was a recognised clinical condition, but that the detailed relations between noise and its effects on hearing were not sufficiently understood for an adequate consideration of hearing preservation and of the problems of compensation.

The detailed terms of reference appear in the text of the report; the basis of the study was the acquisition of specific information on the hearing deterioration caused by exposure to various actual industrial noise environments over periods of time. This required mobile laboratory facilities for the measurement of noise and of hearing. Granted these facilities, including a qualified staff to operate them, and an otologist to carry out the necessary clinical examination of the subjects, the major problem in such work is access to the field situation. With the co-operation of managements, trade unions and the volunteer subjects themselves the work was carried out in the necessary variety of industrial situations. The authors warmly thank the many people who made the study possible.

The objective of the work was to establish a quantitative relationship between industrial noise and the resultant impairment of hearing. The aim was to do this in as broad a way as possible, within the limits of a field study of predetermined duration, so that the results would be generally applicable to industry. The hearing acuity of over 750 people employed in a wide variety of occupations, and exposed daily to noise for periods up to 50 years, forms one half of the main body of the experimental material; data on the noise exposure forms the complementary half.

The work dealt with more or less continuous noise, though of widely differing characteristics: it did not deal with sharp or percussive noise such as that from mechanical hammers. The importance of impulsive noises, and the additional complications that they entail, are recognised, and they merit further study as an extension of the work described here.

As human beings vary greatly in their sensitivity to the damaging effects of noise, the results have in the main to be presented statistically, as average estimates of impairment together with measures of the spread. Statements of averages, on the other hand, are of limited value in assessing individual cases and the central object of the investigation was to assist with the problem of recognising and quantifying the amount of a noise-induced hearing loss in individual cases. This problem is inseparable from any scheme of disability compensation. The results of the work do indeed provide the basis for a systematic diagnostic aid for these purposes; and although completely clear-cut results applicable to individuals were hardly to be expected, the vagaries of susceptibility can be taken into account by a procedure which, if not infallible, provides supplementary evidence in the appraisal of cases.

The investigation was based intentionally on observations of the specific effects of noise on ears free from any other ascertainable cause of impairment, save that due to advancing age. The frequent occurrence, in practice, of complicating factors, for example ear disease or exposure to the firing of weapons, is recognised and the investigation of such conditions would be a natural extension of the work. We also discuss the question of distinguishing between noise and other causes of hearing impairment in the assessment of individual cases, but the investigation did not set out specifically to determine the extent or frequency of occurrence of different hearing defects in the industrial population.

The work had two other main aims, the first of which concerned the setting of noise standards, for broad guidance to industry. The absolute protection of every person's hearing through universal noise level restriction has to be accepted as an impractical target at present, but as a result of the work it has become possible to state precisely, in terms of direct noise measurements or forecasts, the degree of risk inherent in prolonged exposure to the environment. Risk, in this sense, means the percentage of persons whose hearing can be expected to suffer a specified degree of deterioration. The results can

be used, in a flexible manner, to suit the requirements of different administrations upon whom, rather than immediately upon us as authors, rests the responsibility of setting and operating acceptable standards of risk. Naturally, the lower the risk is set, the more stringent the noise requirements, but in difficult situations various devices such as personal dose monitoring can, in principle, be adopted at a certain administrative cost to match the noise exposure to the defined risk.

The third objective relates to the care of individuals unavoidably exposed to loud noise. The basic approach, already practised in a number of industries, is to note any changes of hearing acuity that occur between successive tests carried out at approximately annual intervals. The same method was followed as part of the present investigation and the results have emphasised the limitations of this approach, even with the best of present-day techniques of hearing measurement, used under the specially rigorous conditions imposed in this project. The difficulty is to be certain that small changes are real and not merely due to variabilities in the measurement. The work has pointed the way to improvements, immediate and more distant, which may enhance the usefulness of routine monitoring audiometry. Furthermore, the quite different possibility has been opened up of detecting the sensitive individuals before any actual loss of hearing has occurred. The method is based on experimental evidence that such persons tend to exhibit not only a long-term susceptibility above the average but also an abnormally large auditory fatigue effect. This is measured by the temporary loss of acuity which accrues during a day's work but which disappears, or at least is much reduced, overnight. A measurement of the acuity of fatigued ears under closely-controlled conditions at the end of a working shift appears to be a promising approach to this aspect of hearing preservation, but requires further development.

The data were obtained over the 5 years from 1963 to 1968, during which some 4000 hearing tests were carried out with the aid of the mobile audiometric laboratory, each test being accompanied by a clinical examination. Noise measurements were performed with the aid of the mobile acoustical laboratory and were combined with the occupational records of the individuals tested so as to obtain accurate assessments of the total noise exposure to which they had been subjected. In addition, control subjects not exposed to noise were studied. The results showed that a combined measure of noise

intensity and exposure duration determines the effect on hearing in a manner which can be likened to the action of electrical energy in kilowatt-hours, a low rate of power consumption (kilowatts) for a certain time (hours) being equivalent to a higher rate of consumption for a shorter time. In consequence of this relationship, industrial noise limits for hearing preservation purposes must take duration into account just as much as noise level.

The investigation was carried out entirely by means of pure-tone audiometry, that is, the measurement of hearing acuity in terms of the faintest perceptible level of test sounds in the form of tones of different frequencies. The relationship between such audiometric measurements and the effects on the ability to perceive speech are well known. The broader question of social disability or impairment of function in relation to a person's occupation does not come within the scope of the report, but for illustration use is made of existing criteria for assessing the degree of handicap in these terms.

At the conclusion of the investigation, in 1968, we submitted our findings in a report to the Secretary of State for Social Services, and it is that report, with only minor editorial amendments, which is reproduced here. We hope it may serve not only as a record of an investigation and of its failures and successes as they occurred, but equally as an indication of the more profitable approaches for the pursuit of future studies—for we must emphasise that this complex pattern of cause and effect is only beginning to emerge. But above all we offer our results as a tool for the handling of industrial noise problems, in situations where hearing is, or may be, at risk and we have tried to do this in as practical a way as possible, in a conscious attempt to preserve a balance between academic propriety and engineering utility.

W. Burns
D. W. Robinson
May, 1969

1
Introduction

History

It has long been appreciated that hearing may be damaged by excessively loud sounds, and historical allusions to specific episodes are not uncommon. In more recent years, however, there has been a growing awareness that the continued exposure to noise in the course of everyday work may lead to significant reductions in acuity of hearing. It is true that the obviously more noisy occupations, such as the manufacture of rivetted boilers, have been recognised as a hazard to hearing for many years, but the occurrence of occupational deafness as a result of protracted exposure to common industrial noise has been generally appreciated only in the last few decades.

Investigations in the realm of occupational health in several countries have attempted in field studies to evolve quantitative relations between noise exposure and deterioration of hearing. Clearly the establishment of such relations is essential for the definition of risk to hearing, and for the formation of any code of practice for the control of such risk. The practical difficulties of an extensive investigation of hearing and noise in industry are such that the participation and support of Government is virtually essential.

Discussions on the feasibility of such research were originated in the UK in the summer of 1957 by the then Department of Scientific and Industrial Research. The outcome was a scheme of research submitted in the names of Dr T. S. Littler and the present authors, broadly in conformity with the pattern of the investigation now being reported. These proposals were put forward in 1958 and were approved by the then Minister of Pensions and National Insurance. Following this, we submitted a revised and more detailed programme of investigation and this scheme secured Treasury approval in principle at the end of 1961. Early in 1962 the Medical Research Council and the National Physical Laboratory were allocated the responsibility for carrying out the investigation under the terms of reference set out overleaf.

Terms of reference

(a) To compare the state of hearing of persons with various known histories of noise exposure.

(b) To secure pre-exposure audiograms and to monitor the state of hearing of people throughout the early years of working in noise locations by means of serial audiograms.

(c) To determine, if possible, whether any significant relation exists between temporary and persistent threshold shift.

(d) To relate the physical properties of industrial noises, with particular reference to those experienced by the groups studied in (a) and (b) above, and to determine by statistical procedures the physical features of the noises which constitute an effective set of criteria for measuring exposure as judged by correlation with its effect on hearing.

(e) To obtain data on hazards to hearing and to make recommendations on measures to avoid them.

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Organisation

Formation of joint working group

At preliminary discussions held in February 1962 between the interested parties, it was decided that a working group should be formed which should include representatives of those taking an active part in the project. In order to recognise the mutual interests and responsibility of the Medical Research Council and the National Physical Laboratory it was agreed that this working group should operate under a joint chairmanship from the two bodies. This group was accordingly set up and proceeded to frame the necessary requirements for the investigation in terms of the scientific programme, the provision of the cquipment and the administrative backing.

From the outsct regular meetings of the working group were held at which the scientific approach was evolved in detail, new and unique equipment was designed and its production supervised. Finally detailed relations were established with the various Government Departments concerned with the procedure to be followed in obtaining access to volunteer subjects in industry.

As the pattern of activity emerged and became established, the need for the continuance of the working group declined, and from mid-1965 the policies prcviously decided were implemented directly by Medical Research Council and National Physical Laboratory personnel and representatives.

Guiding principles for the research

It is generally accepted that there are two entirely different approaches to the kind of problem posed by this study, and it may help to set out briefly the division betwecn the two in order that the position that wc have taken may be clearly distinguished. For convcnience wc will call the two the "parametric" and "incidence" philosophies, and it is thc former to which we subscribe. In the study of hearing impairment due to noise, it is common ground to both

these approaches that the absence of any clear-cut diagnostic aid to the identification of permanent noise-induced threshold shift in individual cases forces one to fall back on a series of probabilities. These are based on such direct evidence as the audiogram, evidence which may be slightly less secure such as the supposed noise history, and supporting evidence such as may be elicited by otoscopic and otological examination. The two approaches are, however, distinguished by utilising the available information in different ways.

In essence, the parametric approach is based on the proposition that the fundamental physiological characteristics of the hearing process are essentially the same for individuals. This basic similarity is overlaid by minor differences due to normal biological variability and within these limits therefore the stimulus-response characteristics are determinate and broadly alike for all persons. In practice large departures from this state of affairs can, of course, arise due to disturbing factors including pathology of various origins. The experimental approach is therefore to utilise for investigation only ears which are free from such disturbing factors so far as can be determined. This method has the great advantage that the results, provided they show sufficiently stable tendencies, can in principle be applied to any noise field within the range of the variables encountered in the study. The end-product of the immediate investigation can thus be envisaged as a specific relationship between a physical description of noise exposure and the resulting hearing level with, of course, statistical overtones.

The application of the results obtained according to this viewpoint would take on the following aspects. First a conventional otological examination with a case history is conducted. Then the audiogram of the individual concerned is compared with basic diagrams, or possibly mathematical equations, describing the relations of noise exposure to hearing level, the diagrams giving also the statistical distribution data. An *a priori* probability is thus established that the person has or has not sustained an occupational hearing loss. If there are no other indications and the probability is high, the noise-induced origin of the lesion can be assumed. If the probability is not high, further audiological tests which might conceivably include an administered fatigue (temporary threshold shift) test would be carried out to narrow the probability. At this point we should draw attention to item (c) of the terms of reference; clearly if a close relationship can be shown to exist between the persistent irreversible

threshold shift and the short-term reversible hearing fatigue on an individual and not merely a statistical basis, the relative ease of measuring the latter would provide a most powerful diagnostic aid. Looking still further ahead it might even become possible to use the test prognostically as a part of hearing preservation measures. In addition to the narrowing down of aetiology by these means we should mention also the strong but not infallible clue provided by the shape of an audiogram of hearing level plotted against frequency: the effects of natural ageing, of noise trauma and of certain pathological conditions tend to produce different and characteristic patterns. Finally one would bear in mind that a pronounced hearing impairment in one ear only is a likely but not invariable contra-indication.

So far we have discussed the hearing impairment solely in terms of the measurable aspect, namely the threshold of hearing. We recognise that any rules formulated to determine compensation must entail a broader assessment of disability. A first step is to translate a pure-tone audiogram into terms of impairment of perception of speech, and some research work is available to assist here. To enter more deeply into social disability would go far beyond what we intend by the present "parametric" approach and would raise questions that could not be answered in any general way.

The incidence approach is perhaps more suited to the study of the last-mentioned aspect for, as the name implies, it assumes the existence of groups which are in certain respects homogeneous, e.g. by occupation in a common industry, or by sociological classification. It can be argued with some justification that if research into the noise and hearing relationships is pursued within such a group the very fact of its homogeneity with respect to one or a number of factors is likely to lead to results with lesser deviations than in the parametric approach which seeks to sample as widely as possible from among the variables. However, as we have understood the viewpoint of protagonists of the incidence approach, the history of an individual is not included as a factor except insofar as he has so many years of actual or presumed association with the noises characteristic of a process or industry. This is in sharp contrast to our approach where the history of noise exposure ranks equal with the hearing in importance of measurement, with consequential wastage of large numbers of otherwise suitable subjects for whom the noise cannot be stated within scientifically satisfactory tolerance. Finally, since it is implicit

in the incidence philosophy that the results for one industry cannot necessarily be carried over into another, it would be a monumental task to perform such studies on a wide enough range of industries to permit extrapolation to newly-arising situations or to provide a basis for central government action.

We recognise that to establish the total compensation bill there must at some stage be undertaken an estimate of the incidence of industrial deafness throughout industry as a whole. We believe that the economical way to do this is through sample incidence studies of every main industry. If this is accompanied by a parallel survey of the prevailing noise climates and taken in conjunction with our generalised relationships, there will also be a quantitative basis for making future forecasts of the compensation.

Plan of operation

This investigation is basically a field study of the effects of noise on hearing. It was necessary to find situations in which numbers of persons were occupationally exposed to a suitable noise environment. These subjects had to be available in adequate numbers to provide a valid comparison between the degree of noise exposure and the state of their hearing. For this purpose, clear definitions of the type of noise and categories of persons regarded as suitable were first required. These aspects will be developed later. From the point of view of noise a number of different situations present themselves. The simplest is represented by steady noise which is continuous during the working day and unvarying over long periods of time. Even in this case there are numerous variables resulting in relations of great complexity between the physical stimulus and any possible biological consequences. This situation can be further complicated if the noise, instead of being continuous, alternates with periods of relative quiet or with noise of a different character. Finally, there are noises which, whether continuous or not, are impulsive in nature, as in hammering or forging. It was decided at the outset to concentrate on the first situation, that of steady noise. In the course of the investigation we have made strenuous efforts to find situations of the second kind, but where these have been found the other requirements, in terms of suitable subjects, have been lacking. Fortunately our results for steady noises provide some basis for encompassing the variable type of noise. Examination of the situation with regard to

impact noise has eonvineed us that this requires a separate approach and eould not be satisfactorily handled within the praetical confines and time seale of the present study.

The subjeets in the survey participated solely on a voluntary basis; for the purpose of the investigation only those with ears free from disease (as arbitrarily defined) were aeeepted so that their hearing could be eonsidered to be unimpaired except for the effeets of noise. Certain additional requirements had to be met, e.g. that each person should only have been exposed occupationally to one significant type of noise; other fortuitous noise exposure, for example that of small arms fire, would lead to their exelusion. In addition, an elicited history of uneonseiousness due to a blow on the head or any other faetors which might have produeed an impairment to hearing, resulted in exclusion from the investigation.

Bearing these requirements in mind eertain fundamental considerations and limitations present themselves. The nature of the researeh demands that, for aeeeptable validity, real and measurable deterioration of hearing should be related to the degree to whieh the individuals coneerned had been exposed to noise. On the other hand it was clearly unacceptable on an ethieal basis that persons should be deliberately exposed to noise in order to aseertain permanent effects on hearing, nor indeed should signifieant deteriorations be allowed to proeeed uncheeked for the purpose of gaining information. Speeifie procedures were developed, as indicated below, to ensure that these ethieal aspeets were observed.

In summary, therefore, the problem was to diseover actual situations in industry where noise exposure, in terms of its physical eharaeteristics and its duration, was amenable to preeise measurement. Noise exposure could then be related to the state of hearing on a quantitative basis, in subjeets whose hearing was free from other sources of impairment.

We have taken the view that any differences that there might be between the effects of noise on persons with otherwise unimpaired hearing and on those with some auditory defect eould not properly be elucidated without a clear understanding of the former case. The variety and range of severity of pathological conditions would multiply the requirements of the study several-fold. Although such studies did not feature in our terms of referenee we nevertheless deemed it highly desirable to obtain some information on the question.

The broad principles of our parametric approach can be put into practice along three main lines of investigation, namely:

(a) to measure the hearing of young people before they start work in noisy occupations and then to continue to measure hearing at suitable intervals. This method is known as a "prospective" study.
(b) to measure the hearing of persons who had been exposed to particular noises for various durations (which might be for an appreciable number of years); this method is known as a "retrospective" or "cross-sectional" study.
(c) the subjects under (b) above could also have their hearing measured periodically as in the case of (a). This is referred to as "serial audiometry".

All subjects, as previously noted, were volunteers and the results of the hearing examination were treated in strict confidence by the investigators. In cases of ear defects or disease likely to require further investigation or medical treatment, or of significant deterioration of hearing believed to be due to noise, the individual was informed and consent sought for an approach to his or her own doctor or the works medical officer, to ensure that any of these conditions did not go unattended. Furthermore, noise conditions which were deemed excessive were reported to the factory management concerned.

Population selection

At the outset the working group included a medical statistician to advise on such questions as population sampling. It became obvious, however, at an early stage that normal medical statistical practice in terms of the selection and utilisation of experimental populations, and methods of sampling, had limited application. In fact, the inevitable situation obtained throughout that volunteer subjects were called for, from suitable working populations, and the difficulty of obtaining adequate numbers rendered any sampling procedure inappropriate. The subject population throughout remained essentially a self-selected one. This population was subsequently reduced by the initial screening process, as is noted below. Inevitably, further attrition occurred due to job movements and normal wastage. The feature of initial self-selection therefore must be accepted as an inherent characteristic of this study.

Allocation of work

The distribution of effort for both field work and analysis of the data was conceived as a closely-knit joint undertaking by the Medical Research Council and the National Physical Laboratory. Particular responsibilities for individual aspects fell conveniently into two sub-divisions, predominantly biological and physical respectively. The Medical Research Council assumed primary responsibility for the otological, audiometric, medical and documentation aspects of the project and the National Physical Laboratory for the design, maintenance and calibration of the specialised audiometric equipment, noise measurement, and the major part of the data reduction. The National Physical Laboratory's computing facilities were utilised.

Despite these logical sub-divisions, overall collaboration as originally envisaged has, in fact, been realised in a most satisfactory manner in the various activities of the project and the compilation of the final presentation of the results. In Appendix 3 is a summary of the personnel involved.

Vehicles and equipment

The working group planned and authorised the necessary equipment needed for undertaking the field work concerned with the hearing measurements for the survey.

The facilities required to conduct both otological examinations and audiometric tests were met by the provision of a mobile audiometric laboratory and a mobile consulting room. The specialist design of the former presented a considerable technical challenge, due to the very high degree of sound isolation specified, the need for ventilation, and the completeness of the instrumentation for audiometry and for calibration of the audiometers. This mobile audiometric laboratory consists of a commercial production chassis on which is mounted an acoustically insulated body, having within it four sound insulated booths associated with self-recording audiometers permitting simultaneous audiometry for four persons without interference from any anticipated, or encountered, ambient noise. Complete calibration facilities for the audiometers were also installed. The details of the acoustic specification, design features, and measured acoustic attenuation of this vehicle are given in Appendix 4.

A suitably modified commercial caravan served as office, waiting and consulting rooms. In it the necessary case history was taken and otological examinations performed before the subjects' hearing was measured. A Land-Rover was provided for towing the mobile consulting room and for general mobility of staff.

The equipment for sound measurement was housed in a mobile acoustical laboratory, designed and maintained by the National Physical Laboratory for general acoustic purposes. This is described in Appendix 5.

3
Data acquisition

Selection of factories

In view of the nature of this project, which demanded access to a large variety of industrial undertakings and called for a high degree of co-operation at all levels, it can be appreciated that a considerable administrative effort was required for the successful prosecution of the research.

The assistance of the Ministry of Labour was sought to obtain, through H.M. Factory Inspectorate, details of factories where a suitable noise environment was thought to exist. The details so furnished were scrutinised, and arrangements made for an approach to be made to those firms whose factories appeared to offer suitable conditions both in terms of the level of noise and the number of persons exposed. These firms were then approached by the Ministry of Labour through H.M. Factory Inspectorate or the Confederation of British Industries. Where a firm expressed interest in the project, a preliminary visit was made to the factory in company with the H.M. District Inspector of Factories, and the purpose and extent of the survey discussed with the management.

If the factory was judged to meet the needs of the survey, a date for a visit by the audiometric field team was arranged, and the management provided with copies of an agreed "handout" (Appendix 6) for circulation to their employees when asking for volunteers to undertake the tests. The H.M. District Inspector of Factories concerned was asked to inform the representatives of the appropriate trade unions of the intended visit.

The co-operation of management and employees had to be obtained in order to ensure that the volunteer subjects were available for hearing measurements before the start of the day's work. In some cases measurements were also made immediately before, or at, the cessation of the work period. Finally agreement had to be obtained for the repetition of this procedure at approximately yearly intervals until sufficient data had been accumulated in order to attempt to observe the trend of deterioration, if any, of each person's hearing.

The method of selecting the factories for inclusion in the research programme, and an outline of the difficulties encountered in obtaining access to young people (school leavers) immediately before starting work, are given in Appendix 7.

Pre-selection of subjects

Experience gained during the initial visits to the first nine factories selected for inclusion in the survey, showed, as had been anticipated on the basis of our previous experience, that only a relatively small proportion from among the personnel volunteering to be examined were suitable for inclusion in the study. Many had either been exposed to other types of noise elsewhere, or had some ear defect, or had a history of previous head injury, and thus had to be excluded for these or other reasons.

It was decided that wherever possible some form of pre-selection from among volunteers would be desirable, and firms were invited to conduct a check on personnel with a view to withholding from abortive examination and test those

(a) whose present noise exposure was not amenable to quantitative description
(b) who had served in the armed forces, or had been exposed to gunfire, or whose past noise exposure was different from that of their present occupation
(c) who were known to have existing or previous ear disease or abnormality
(d) with language difficulty.

The effect of the application of this initial selection inevitably varied somewhat between firms, and it was found to be more effective where the assistance of a full-time medical officer was available. In any case, a full history elicited by a questionnaire, and a clinical otological examination, remained essential parts of the procedure. This preliminary selection contributed greatly to a saving of effort in the final selection process.

The volunteer personnel were interviewed by a member of the field team and broad details of their work, previous employment, possible earlier exposure to noise, including gunfire, or any occurrence which might possibly have had a bearing on their hearing acuity, were obtained. This interview was undertaken each time personnel

were tested, immediately prior to a clinical otological examination. The recorded details were then taken into account in reviewing the results of the subsequent audiometry. It is worth remarking that later interviews occasionally brought to light factors which had not been previously disclosed.

Otological examination

As has been indicated previously, audiometric tests were never performed in isolation, but always in conjunction with a clinical otological examination. Such an examination is a necessary accompaniment of audiometry for the latter to be valid.

At the outset, the working group, guided by the member otologist, laid down criteria for acceptability on clinical otological grounds: these together with the method of examination used are set out in Appendix 8.

It was obviously essential that the yardstick of "normality" should remain unchanged despite the passage of time and unavoidable changes of otological personnel. This objective is neither easy to specify in all particulars, nor to attain with certainty. Every effort was made by the otologists to maintain continuity and to preserve the original clinical criteria. The fairly high clinical standards adopted to qualify for "normality" assisted in minimising the unwarranted inclusion of marginal cases.

Of the volunteer subjects coming forward through the pre-selection procedure, the clinical examination in fact resulted in eliminating about 11 %.

As previously noted, however, some data on cases originally classified as unacceptable because of pathology, exposure to gunfire noise, or previous concussive head injury, were studied separately to supplement the main study, and these categories are described in Appendix 14.

Audiometry

The audiometric facilities were planned from the outset to give the highest standards of accuracy and reliability (compatible with the nature of the investigation) which the present state of development of pure-tone audiometry would permit.

With this in mind the audiometry for the survey was performed with a type of self-recording audiometer (Rudmose ARJ-4) modified at the National Physical Laboratory. These modifications include adaptation for the use of the type of high-quality earphone (Standard Telephones and Cables 4026A) normally used in the UK as a standard, and a device for interrupting the tones. This second modification was adopted after preliminary trials suggested that this gave a rather easier signal detection task to untrained subjects, without prejudice to the measurement of hearing levels. The audiometric vehicle provided full calibration facilities to ensure the continued accuracy of the audiometers. For normal clinical purposes such calibration might be carried out at intervals of perhaps up to one year, but for the purpose of the survey a calibration of the audiometers was carried out on every day on which they were used for audiometric measurements. The records show a remarkable constancy of performance.

The audiometers provide information in the form of a graphic record on a card marked with co-ordinates for hearing threshold and frequency of the test tone.

The traces were interpreted by two independent observers, using a mechanical cursor, to average the vertical excursions of the trace, thus providing as consistent a method as possible of estimating the threshold for various frequencies, short of fully automated equipment. Where a discrepancy of 2 dB or less occurred in the two judgements, their mean was adopted. If the discrepancy exceeded 2 dB, the trace was re-assessed by the two observers in conjunction. This is part of the essential raw data of the investigation. The technical details of the modifications and calibration methods for the audiometer equipment are given in Appendix 4.

Noise exposure

From the outset we took the view that the determination of subjects' noise exposures should weigh equally with the audiometry, and that the noise exposures would require as accurate a knowledge as possible both of noise levels and of exposure histories.

The equipment consisted principally of the mobile acoustical laboratory described in Appendix 5, supplemented by an estate car fitted with measuring apparatus for use where the facilities of the

larger vehicle were not needed. At the time of the authorisation of the investigation, this equipment was in the design stage for general acoustical and noise studies on the research programme of the National Physical Laboratory. Adaptations were accordingly made to suit the requirements of the present investigation.

Although, as we have stated, our aim has been to concentrate on steady noises we found in practice that rigid adherence to this prescription would have ruled out all but a handful of the 32 factories which were otherwise suitable. The first few factories visited were, in fact, those wherein the least steady noises existed which was perhaps a fortunate accident, inasmuch as the measurement procedures were evolved to meet these cases and proved to be adequate in scope to deal with all later visits.

A full acount of the organisational and technical conduct of the noise measurement is given in Appendix 9. Briefly the aim was to effect a suitable compromise between elementary noise measurements which would have offered little or no scope for investigations such as spectrum-dependent effects, and an excessively complex set of data which it would have been difficult to utilise effectively. A further consideration was the ultimate use of a computer to study the relations between noise and the audiometric results, and with this in prospect it was essential to express all the noise environments in similar physical terms. Variations of noise level had also to be accommodated, thus necessitating time analysis as well as spectrum analysis.

The estimation of exposure history depended in the first instance on the subjects' questionnaire responses, and in detail on a study of the factory layout, work methods, any changes that had occurred to plant and machinery, and employees' records, obtained in consultation with factory managers and personnel departments, and sometimes by direct interrogation of employees. Doubtful cases, for instance those with previous employment in factories where the noise might have been comparable or greater in level, were ruthlessly eliminated. A small number with a clear history antecedent to a recent date followed by quiet employment were accepted with appropriate assignment of the period in noise; these subjects were not included in serial audiometry.

Exposure durations were reckoned in units of one calendar month, which may be taken for practical purposes to mean 160 hours of actual noise exposure per month.

Compilation of master ledger

The basic components of the data of the investigation are, as we have noted, the noise exposure and the hearing level of each person. To complete these statements a quantity of subsidiary data is needed. Every individual's personal data must include the following items: serial number; name; age; sex; noise level in dB(A) at 2% and 50% on-times (Appendix 9); sound pressure level in the octaves centred at 63, 125, 250, 500, 1000, 2000, 4000 and 8000 Hz; duration of exposure; hearing level in each ear at the audiometric frequencies 500, 1000, 2000, 3000, 4000 and 6000 Hz for each occasion (with dates) on which audiometry was performed, including temporary threshold shift data where applicable. Subject data were grouped by firms, and included any identification number provided by the employer to facilitate locating individuals at a later date when, for example, further details of his noise history might be enquired into. In addition the otological data, personal history and audiometer cards were retained for each person.

The number of subjects included in the final data-producing part of the investigation is about 1000, and the total number of audiograms was over 4000, so that the complete pool of information contains in the region of 100,000 items. The storage of the numerical parts of this information was accommodated in a computer system. However, we felt that the scale of the investigations, the need for rapid and direct access, convenience, flexibility and portability in the initial recording of the data, could best be served by a conventional manually written loose leaf ledger system which became the definitive store of the information. One of us had such a ledger format in existence, and this was found to be admirably suited to the needs of the initial data recording and easily accommodated all the above information relating to each person in the survey.

In all subsequent stages the data were extracted, usually for preliminary assessments on the desk calculator, and later for the construction of appropriate computer programs.

4
Results

Retrospective studies

The aim of the retrospective study may be described as the elucidation of intrinsic relationships between the several variables: noise level, spectral distribution, age and hearing level. It is of necessity approached by the methods of numerical statistics. Field data were allowed to accumulate until we had some 400 results before it was felt worthwhile to analyse them systematically.

At this stage definite indications emerged. The scatter of individual hearing levels was large, and increased within groups exposed either to louder or more prolonged noise, but was appreciably reduced if an allowance was made for the ages of the subjects. This was consistent with the expectation that ageing and noise are at least partly independent and therefore additive. It was also found that the measure of noise level L_{A2} (see Appendix 1), compared with various other physical measures, was the most relevant in the sense that the hearing levels within groups classified by this measure alone showed a progressive increase with noise level and with the duration of exposure.

Computer programs were prepared to examine the data more systematically having regard to these preliminary observations. Meanwhile additional field data were acquired and submitted to a thorough examination in the light of the otological and other particulars given by each subject. The computer programs were run on the resulting total of 581 persons.

In the course of this analysis it became noticeable that the age-corrected hearing levels of persons, subjected to a certain noise level for a certain time, followed much the same course as those of others in higher noise levels for shorter times. It is, of course, a trivial observation that any specified combination of noise and time leading to a certain final state of hearing could be matched by another combination causing the same final state. It is much less evident and, we believe, of fundamental significance that there exists a combined measure of noise intensity and time such that the equivalence holds at

intermediate stages, not merely the final state. Appendix 11 sets out the detailed reasoning that led us to the particular and very simple relationship which permits the definition of a single composite noise exposure measure which we term *noise immission*. It turns out that this quantity is just a frequency-weighted measure of the total sound energy impinging on the ear throughout the whole exposure period. For convenience we more often refer to the related quantity, *noise immission level* (NIL) in decibels; this bears the same relation to noise immission as does any other physical quantity expressed in decibels to its parent magnitude.

With the aid of this finding we could intensify the search for intrinsic relationships between noise exposure and hearing level since the number of independent variables was reduced, basically from three to two. At this stage the computer results confirmed the preliminary findings regarding the separability of age and noise effects and the advantage of the measure L_{A2}.

Up to this time it had been sufficient in a statistical sense as well as convenient for least-squares computer programming, to approximate the relationships between noise, time* and hearing level by simple functions, namely straight lines and parabolae. Refinements now suggested themselves; moreover further field data were to hand making the final total of 759 persons. It was now perceived that the course of hearing loss at different frequencies followed similar patterns; it was also discovered that the scatter of results followed an equally orderly pattern. These two findings were, moreover, seen to be closely related to each other, and together they permit the intrinsic relationships to be viewed as variations on a single theme. The final steps of the data reduction are of a rather mathematical character out of place in this Chapter; full details are given in Appendix 10. It is only necessary to remark here that the experimental results in their entirety can be summed up in a formula involving only one variable with two parameters. One of these is related to the audiometric frequency, the other to the percentage of persons concerned.

By means of this formula, which is simple enough to carry in one's head, or by the use of an equivalent nomographic chart, it is a straightforward matter to perform any desired prediction or manipulation of the variables. A direct application is to estimate the percentage of persons whose hearing level can be expected to exceed a

* Strictly, the logarithm of exposure duration.

specified value at a given frequency (or combination of frequencies) as a result of exposure for a stated period to a known noise level. Alternatively the formula will answer the converse question: what noise level should not be exceeded in order to ensure that a stated percentage of persons should not suffer noise-induced hearing loss greater than a specified amount?

In Appendix 15 we discuss the relationship of these results to other research work on noise-induced threshold shift. We tend to predict smaller losses, but we should emphasise that this is in the expected direction, since we have taken elaborate precautions to exclude any of a large number of other possible contributory causes of deafness, in accordance with our basic research aim. We discuss the important but ancillary question of total hearing level in cases with added pathological or other impairment in Appendix 14.

A further computer programme was devised to establish the range of spectral distributions that would be sufficiently well characterised by the single overall measure L_{A_2}. More complicated methods for measuring and expressing noises have been proposed from time to time as desirable or necessary. We had routinely accumulated throughout the investigation several measures of each noise (see Appendix 9), including octave-band spectra. It had not been possible to utilise this more detailed information in an efficient manner, however, until the general nature of the relationships between noise exposure and hearing loss had been established. With the aid of these supplementary noise data we show that a single measure, rather than sets of band sound pressure levels, is adequate to characterise the hearing damage potential of the great majority of noises even though they may have widely differing spectral distributions. Moreover we find that the shape of the average noise-induced "audiogram" is independent of the spectral distribution within wide limits, and invariably exhibits the well-known "4 kHz dip". A frequency response marginally different from the A-weighting emerges from this analysis as the optimum design characteristic for the relevant noise measuring system; but so little does it differ from, and so well-established in general acoustic usage is the A-weighting curve, that we confidently recommend the latter.

The time course of the pure noise-induced threshold shift turns out to be extraordinarily rapid at first and the rate slows down progressively throughout the whole of the subsequent exposure. This finding is supported by the results of the serial and prospective

studies. The curve is smooth, and shows no sign of suddenly flattening off at the 10 or 15 year mark, as has been suggested by other workers. When the effect of ageing is included, the curve has of course a stronger upward trend, finally becoming steeper as the presbycutic loss eventually overtakes the noise-induced loss.

An interesting rule of thumb can be deduced from the curves which applies with fair approximation to any exposure exceeding 5 years in duration. A glance at Fig. 10.1 will show that the increment of hearing level is about 0·8 dB per year for high tones, irrespective of noise level. The level attained in the course of the first 5 years, on the other hand, depends very strongly on the noise level.

Serial and prospective studies

The direct observation of hearing losses by means of serial audiometry appears at first sight to have advantages over the retrospective type of study. In the latter, any conclusions about the time course of hearing deterioration have of necessity to be stated statistically. In the former, the same persons reappear at successive tests so that threshold shifts are identified with individuals even though in the aggregate they might be described statistically. Thus one should end up with distributions of hearing levels corresponding to a series of exposure times by either method, and the results should be essentially similar. The great difference is, however, that from the serial study there would be a one-to-one correspondence between elements of each distribution which is entirely lacking from the other method. This is particularly desirable information for the study of early deterioration of susceptible ears.

For these reasons it was hoped that the serial study would form an important, if not the key, part of the investigation as a whole. Originally the retrospective survey was foreseen as filling the secondary role of forecasting hearing levels in cases of exposure duration beyond the 4-5 year limit of the serial studies. In the light of experience both studies assumed a different significance. The highly coherent results obtained from the retrospective survey far exceeded our early expectations and culminated in charts and formulae for the statistical prediction of noise-induced threshold shifts over a very wide range of noise exposures from nil up to many years at high noise levels. By contrast the serial study ran into problems more severe than we had envisaged. One of these was the scientifically extraneous difficulty of

locating enough cases of persons with little or no previous noise exposure, or of locating them rather late in the course of the investigation (see Appendix 7). The number of subjects meeting the requirements of a true prospective study remained disappointingly small to the last, and no cases at all could be found in sites with really high noise levels. Large numbers of serial tests were indeed carried out (see Appendix 12) but for the most part in the experimentally unfavourable circumstance of there having been previous noise exposure significant in amount compared with the increment received between tests. A second and more deep-seated problem exists, however, and would have beset our endeavours no matter how successful our quest for unexposed subjects might have been. This is the influence of random errors in the audiometry which all but swamp the noise-induced part of the threshold shifts. Even with the safeguards of precision equipment and impeccable control of the testing, these errors must be regarded as ineradicable in the practice of pure-tone audiometry as it is today, unless one is prepared to perform numerous repeat measurements. Considerations of work schedule interruption, of maintaining the co-operation of subjects and of management, not to mention equipment availability and cost, ruled out such possibilities from the routine of our investigations, although the matter was argued many times by the working group.

It is necessary to draw from our data some rather disquieting conclusions about the significance of apparent hearing level changes in annual serial audiometry such as might be administered routinely in industrial hearing conservation schemes. This is perhaps the most important lesson to be learnt from this part of our investigation even though it is rather discouraging in character. The limitations are discussed further in Chapter 5 and Appendix 12.

On the positive side, we have shown that the hearing losses accruing during the course of the serial study are, save for the random errors, quite consistent with the expectations derived from the retrospective survey as, of course, they should be. But it is important to note that the serial results by themselves would certainly not have permitted the determination of well-defined trend curves in the way that was found to be possible with the retrospective data.

In practice an apparent improvement in hearing is observed almost as often as a loss. The former can reasonably be dismissed as having nothing to do with noise and therefore erroneous or at least as of adventitious origin. The same cannot be done with apparent losses

since these may well be genuine. Though it is clear in some cases that apparent losses are unreal, in the great majority there is no sure way of telling true from false. It follows that to eliminate negative losses from the results would give an upward bias to an unrealistic extent. To retain them, therefore, is essential and we have found no way out of the dilemma of handling a mass of data much of which obscures the effect under investigation.

By statistical tests we have shown a significant correlation between the rate of deterioration of hearing and the hearing level already attained. This relationship, it should be emphasised, applies to the early stages and is consonant with the mathematical model derived from the retrospective study. It has no connection with the question of the slowing up of the deterioration rate when high hearing levels are reached.

Full details of the prospective and serial studies are contained in Appendix 12.

Temporary threshold shift studies

The variability between individuals of the hearing loss due to noise exposure is one of the main obstacles to prediction of hearing loss from a known noise exposure in a particular individual.

The work described elsewhere in this report has evolved means of estimating the degree of hearing deterioration likely to be caused by a given noise exposure, in the form of a distribution in the exposed population. The natural extension of this is to attempt to predict, in the event of continued occupational exposure to his present, or a subsequent noise, where in the expected range of hearing impairments the values for a particular individual would be likely to lie. The merit of such predictions would, of course, be in the ability to advise on the probable degree of susceptibility to occupational hearing loss, and hence on the suitability or otherwise of a particular person entering a given noisy occupation.

Various tests have been suggested by different authors for this purpose, using some form of measurement of temporary threshold shift (TTS), on the hypothesis that this can provide an indication of the degree of susceptibility to permanent impairment of hearing due to noise exposure. However, such tests do not rest on specific experimental verification of the validity of this hypothesis, for individuals.

It has been found, and confirmed in this study, that TTS of groups

of persons appropriately measured, is quantitatively similar to the average presumed noise-induced hearing loss in ears which have sustained about 10 years of continuous daily occupational exposure to the same noise. This relationship means that, for averages of groups of persons, the same noise will produce certain degrees of temporary and related degrees of permanent threshold shift. The relation does not imply any particular type of behaviour with respect to TTS and to occupational hearing loss in the case of individuals, and it is the individual case which we have tried to examine. In order to test the characteristics of the individual ear with respect to its susceptibility to TTS and to occupational hearing loss, various procedures could be devised, but they are beset with serious obstacles.

Logically, the procedure could consist of the measurement, in ears not previously subjected to significant noise exposure, of the TTS occurring after the first day of work in a particular noise, followed by normal occupational exposure over a period of about 10 years, when the permanent change would be measured. In the first place this lapse of time could not be accommodated within the time scale of this project. Further, the number of subjects who could be audiometrically examined before starting work (e.g. school leavers), and who would thereafter remain in the same job, and thus exposed to the same noise, for a sufficient duration, has been found to be extremely small. Finally, in this survey, subjects have not been deliberately allowed to acquire significant hearing losses merely for the purposes of the investigation, so that the procedure would, in any case, be unacceptable according to our code of conduct of the work.

We considered that any fresh experimental approach should consist, at least initially, of the simplest and most straightforward procedures, limited in technical scope to conventional audiometry of good quality and compatible with the implications of an industrial situation. We consequently examined the nature of the information which could be derived from single measurements of TTS in an individual, following exposure for a normal working day to his particular occupational noise. At the same time, the necessary hearing level measurements made before the start of the day's work gave the presumed degree of occupational hearing loss already sustained by the same person as a result of exposure to the same noise over a known period of time. These measurements fitted into the programme of the retrospective part of this study. As an additional objective, we aimed to investigate directly the relations between TTS

and any increments of occupational hearing loss detected in the course of serial audiometry.

The details of the investigation of the relations of TTS to occupational hearing loss and to serial threshold shifts are described in Appendices 13 and 12 respectively.

Briefly the procedure was to define indices of susceptibility to TTS and noise-induced hearing loss, for each individual, and to ascertain whether any relationship existed between the two.

It is obvious that a wide range of frequencies, or combined averages of frequencies, could be used at which to derive the indices. A number of combinations were examined (see Appendix 13). The most favourable combinations, i.e. those giving the highest correlation coefficients, were derived from the lower audiometric frequencies for TTS and from the higher audiometric frequencies for noise-induced hearing loss. The relation between them was a direct one in these cases, and although the values of the correlation coefficients were not large, the higher values were statistically significant for the groups of subjects used in the correlation. Procedures designed to examine the validity of this relationship are also described in Appendix 13.

From these investigations it is possible to conclude that higher susceptibility to TTS tends to be associated with higher susceptibility to occupational hearing loss, and vice versa. The fairly low values of the correlation coefficients indicate that other factors are operating. This we know to be true, for instance in the variation inherent in the technique of air-conduction audiometry, and in the uncertainty of the hearing level of the subjects before occupational exposure began. The obvious question arising out of these findings is whether TTS can be used to predict the degree of susceptibility to occupational hearing loss.

We have examined the correlations critically to assess their value in any possible practical predictive test. The conclusion is that, although a measurement of TTS after one day's work in noise is in principle capable of revealing the individuals who might be expected to show higher degrees of occupational hearing loss, the inherent variability of audiometry conceals the finer structure of the relations. All that can be said of a test using only the data available in the above form, obtained as it was in the course of the survey, is that a number of individuals can be identified in any given group who can be expected to belong to the more susceptible half, but not necessarily to comprise the entire more susceptible half.

Our investigations were also directed to an attempt to determine whether those subjects showing higher rates of deterioration in the serial audiometry also showed higher degrees of temporary threshold shift. Again, this apparently direct and straightforward comparison yielded, at best, a correlation coefficient having a significance value of $P=0{\cdot}10$, which implies a higher probability of a false result than at the conventional 'significant' level of $P=0{\cdot}05$.

To sum up, we have succeeded in arriving at certain basic relations between TTS and aspects of permanent noise-induced hearing loss, and have sketched out a feasible approach to prognosis. Unfortunately, we are unable to proceed to the final logical step of defining a predictive test, based on TTS, of sufficient reliability and precision to be sure that it will identify uniquely those persons at greatest risk. However, we believe that our studies have taken us further towards a practical test than has been achieved hitherto. There seems little doubt that, once again, our progress towards greater precision in these relations has been impeded to a disappointing extent by the inherent imprecision of data deriving from conventional pure-tone air conduction audiometry. Clearly further effort should be directed towards a realisation of a fully practical predictive test using the information now obtained.

Pathological cases

Our approach to the overall problem, as delineated in the terms of reference, we have already explained. Our parametric method utilised subjects free from hearing impairment other than that deriving from advancing age or from industrial noise exposure. We do not thereby imply that such a condition is applicable to the generality of persons employed in industry. In the population at large, a number of factors, including ante-natal or hereditary hearing defects, the legacy of ear disease, the presence of active pathology, or the result of non-occupational noise exposure, will each tend to increase hearing levels and to complicate the picture of occupational hearing loss, if such exists. In consequence, in a proportion of persons, the actual hearing level recorded after a particular exposure will be compounded of the effects of noise and whatever other factor or factors are operating. Thus, on average, in any unselected industrial population, the apparent noise-induced hearing loss, deduced from hearing level measurements by allowance for age, will be greater than our pre-

dictions on the basis of noise exposure. This disparity would of course vary in proportion to the 'pathology' component present, and would disappear altogether if the population, as did our definitive population, lacked pathological elements.

Should it be necessary to ascertain the magnitude of the pathological component in terms of its effect on hearing level, it would be necessary to conduct an incidence study using conventional statistical sampling techniques. In the present study this approach had no part, for reasons already explained, and the effect of pathology was not our primary concern. Nevertheless, against the background of the main study we included a small number of cases, generally described as 'pathological'. These included categories of individuals with conductive hearing loss, vertigo, sensorineural hearing loss (other than noise-induced, traumatic, or associated with vertigo), gunfire exposure, or a history of unconsciousness due to head injury. The vertigo group was so small in numbers as not to justify further consideration.

Normally, a comparison between the effects on hearing of these conditions, and an uncomplicated noise exposure, would require an age-matched and exposure-matched control population. This would present great difficulties. Fortunately, the relations which we have been able to establish between noise exposure and hearing loss (Appendix 10) are well suited to supply the necessary comparison. Indices developed in the course of the work include one which relates the observed to the calculated age-corrected noise-induced hearing loss. By the use of this index the hearing of any individual can be compared with the expected distribution of values on the basis of changes accruing only from the effects of age and of noise exposure, provided the latter is known.

The means adopted and the results obtained from this comparison are given in Appendix 14. While the numbers in the categories with conductive hearing loss or perceptive hearing loss are small they are sufficient to provide an illustration of the approach. The results demonstrate an elevation of hearing levels above those to be expected in non-pathological cases. In the case of the categories with gunfire noise exposure or with a history of head injury, the median values are virtually equivalent to those of our definitive population. The conclusion which we reach in the light of this small exploratory study is that the index used is well suited to an examination and assessment of the combined effects of noise and other hearing

defects, and might in some circumstances be of use in indicating pathology. The sample size of those primarily exposed to gunfire noise or having a history of head injury is not large, but the results indicate that, at least in the conditions of our investigation, on average these effects are negligible. Whether this conclusion could be transferred to general use in the assessment of disability from noise exposure is considered more fully in Appendix 14. Cases of noise-induced hearing loss clearly differ from the pattern of conductive hearing loss, or from other types of sensorineural hearing loss, and cases where noise damage coexists with these other conditions must be considered individually.

5
Discussion

We may now take stock of the situation to which the work has led us; a number of aspects merit comment, and for this purpose we refer back to our terms of reference which appear on page 2. Taking these in turn, the situation at the conclusion of the investigation is as follows.

(a) This objective has been completely realised in respect of steady noise environments, and all practical applications have been fully met.

(b) This has been done; the results confirm the pattern elicited from (a) and have reinforced the need for caution in the interpretation of monitoring audiometry. Even in the exceptional conditions of accuracy of the audiometry of this investigation it is clear that further improvements in technique need to be sought in order to enable more reliable measurements of hearing to be obtained in the course of audiometry in industry.

(c) A positive relation has been found between TTS and hearing loss or rate of deterioration attributed to noise. For reasons similar to those operating in (b), a practical prognostic test still eludes us. In the present state of pure-tone audiometry it appears not to be a fully practical proposition, although it is possible that in the future such a test may be evolved. The likely lines which it might take have been sketched in Appendix 13.

(d) This has been satisfactorily accomplished, with a greater degree of final simplicity than might have been expected, at least in respect of continuous noise.

(e) The outcome of (a) has provided a very large expansion of knowledge on the relations between noise exposure and hearing impairment. The result is that it is now possible, with confidence, to associate a particular noise exposure with a particular statistical distribution of degree of impairment from this cause, in an exposed population.

These general observations contain a number of more detailed, but important, aspects which we now consider.

General relation of noise and hearing

Our original contention that the "parametric" approach best suited the circumstances has been justified. Thus, to a given noise environment can be ascribed, simply and rapidly, definite properties which, taken in conjunction with the duration of exposure, enable specific degrees of hearing loss, distributed in a particular way over the exposed population, to be predicted. The administrative determination of permissible exposures is no longer tied to the acceptance or otherwise of a single noise level or set of rules implying a single, and hitherto arbitrary and often undeclared, degree of risk. Instead there is a choice, extending over most of the range of possible working noise environments, each having its onw implications of the degree of risk as a statistical distribution. One might, for example, visualise circumstances involving a high noise level for a strictly limited duration; or a series of different levels of exposure sustained consecutively. In these cases, different daily exposure rates can be allowed; they can be summed up in a meaningful manner and, if need be, records kept which would ensure the protection of individuals during such episodes and for the future.

The most suitable noise measure for general use has turned out to be a weighted sound level not far removed from the standardised dB(A) scale. A small superiority rests with the statistical derivative, the level L_{A2}, which is the level in dB(A) exceeded for 2 % of the time; but for most purposes the unqualified dB(A) reading may be employed. This confers great simplicity on the assessment of noises, and its wide applicability has been shown (Appendix 10, section 4). It may be asked what limits there are to the employment of dB(A) as a sound measure. If we confine ourselves to the range of spectra we encountered, there are virtually none, but we are conscious of the need to state some limitation. Accordingly, we define the limits of use of dB(A) as applying to spectra broadly described as not exceeding a slope of 5 dB per octave, in either direction, within the frequency range covered by the octave bands centred at 63 and 8000 Hz. A watertight definition giving expression to this principle and encompassing the many types of irregularity exhibited by practical noise spectra is out of place here. There may thus be doubtful cases, but for spectra manifestly transgressing these limits, or containing peaks outside this range, we do not make firm recommendations on the basis of the present work. Among our reasons for stating these

limits, which in themselves go little beyond our experimental compass, is our evidence that the A-weighting is not quite optimal and this most likely results in an underestimation of the damaging effects of noises with strongly falling spectra. Our evidence for the possible advantage of B-weighting is, however, too slender in the face of other considerations to justify a major shift of emphasis to dB(B). Nevertheless, if evidence accumulates pointing to a superiority of the latter measure we would readily consider a revision, within our general formulations, of our present recommendation, if our predictions could thereby faithfully embrace a still wider range of acoustic conditons.

The description of noise exposure by a compound expression embracing noise level and duration, which we designate noise immission level (NIL), is an essential step in our formulations. It is based on the finising that the equal-energy concept applies in the respect that repeated daily exposures for about one month upwards are equivalent from the aspect of resulting permanent threshold shift provided that the A-weighted sound energies that they represent are the same (Appendix 11).

For the practical administration of assessment of hearing loss in individuals, the question of separability or otherwise of the effects of noise and of advancing age is important. Although the literature is not unanimous on this point, it has been customary for some time to assume that deteriorations from these two causes are inherently different phenomena whose effects are essentially independent of one another, and therefore additive in terms of hearing level: the concept is of a chain of mechanisms in tandem, any or all of which may suffer some attenuation, the total resulting threshold shift being the sum of the component attenuations. There is evidence from other work that presbycusis is a manifestation of a disseminated process affecting the entire auditory pathway including the conductive pathway of the ear, whereas noise is believed to exert its detrimental effects on the hair cells and associated structures in the organ of Corti, and is thus comparatively localised. This view sanctions the effective separation of the actions in the manner described above. We subtracted a presbycusis correction in this way, though of necessity this correction had to be an estimate applied indiscriminately to all individuals, and our data in no way contradict the assumption.

As remarked earlier, our hope was that the parametric studies would yield a broad and generally applicable picture of the stimulus-

response characteristic reflecting the behaviour of the hearing mechanism in the presence of noise. The inherent orderliness, and even elegance, of the relations revealed have exceeded our anticipations. These relations suggest an underlying similarity of a particularly simple kind between the behaviour at different frequencies, between sexes, and among persons of different degrees of susceptibility; the various factors mentioned can be accommodated with considerable fidelity by means of translations along a decibel scale of a unique basic curve of age-corrected hearing loss.

It must be remembered that experimentally-determined relations are bound to exhibit some departures from any idealised model. Such departures can be expected to occur by the vagaries of the self-selection process in which the longest histories of noise exposure may tend to be associated with persons in the better states of health and hence possibly with better hearing. We thus feel that if degrees of confidence are to be ascribed to different parts of our diagrams, it is possibly in the middle and lower levels of noise immission that the highest validity resides.

There are other aspects which need qualification. In most cases, these might be resolved by further work adapted to a different and in general smaller scale of activity than that of the present study. The first of these concerns noise which lasts for less than the entire working day. This is not an uncommon condition, but the most energetic quest failed to reveal examples which were compatible with our experimental requirements. The difficulty arose in such aspects as erratic time patterns of noise and relative quiet, variability of the noise characteristics during noisy periods, and the near-impossibility —or so we concluded—of finding people who, for a number of years had sustained some orderly pattern of interrupted noise, or were likely to do so. We are thus unable to state with assurance the effect of work days less in duration than a normal 8 hours, or of some complex pattern of exposure of a discontinuous nature.

To deal with such circumstances various courses are open, none of them free from possible criticism, for practical application. The first is to assume that the equal-energy principle is applicable down to brief periods of time in the order of minutes. If this assumption is incorrect it at least has the merit of resulting in an over-conservative assessment of risk, that is to say if it errs it errs on the safe side. We appreciate, on the other hand, that undue conservatism would not be regarded as an advantage by an industrial management faced with

a borderline hazard. Another alternative is to accept that a given temporary threshold shift, no matter how arrived at by the cumulative effects of a working day, whether this be in steady or intermittent noise, faithfully mirrors the long-term effects of that pattern of noise. For convenience we may refer to this as the equinocivity principle. To apply it, one would utilise the considerable mass of published data on temporary threshold shifts derived from laboratory experiments. In comparison to the equal-energy principle, this procedure is permissive of higher levels of noise provided they occur for short periods or are separated by substantial "recovery" periods of relative quiet. We must point out that our findings on the existence of a positive relationship between individual susceptibilities to TTS and PTS, on the basis of continuous whole-day exposures, have no direct bearing on the equinocivity principle, except that in a broad sense the higher the degree of association that can be shown to exist between manifestations of the two phenomena the more credible the principle may appear to be.

For a solution to this dilemma, it is necessary to invoke other than audiological considerations; the practical limitations of different courses and the equally important problems of their standardisation and implementation must be recognised, in reaching an engineering type of solution. There are undoubtedly some circumstances in which it may be practicable to perform monitoring TTS measurements on work people on a sufficiently wide scale to merit reliance on the equinocivity principle, whilst recognising that it remains an untested hypothesis. In the ideal case of this kind, the physical assessment of the noise exposure becomes almost superfluous except for control purposes. But there remain difficulties in the case of intermittent noises, notably the proper determination of the appropriate post-exposure time for the measurements. An incidental advantage of direct TTS measurement that has been pointed out is that the TTS itself represents a potential social handicap to the sufferer if it does not recover during his leisure time. This undesirable aspect could, however, be guarded against by the use of principles of conservation without explicit involvement of TTS. The great majority of existing noise situations, as well as all cases of future planning, do not lend themselves to solutions involving direct personal measurements of TTS, and for these and other general purposes it seems to us that the overwhelming advantage lies in the adoption of a solution based on the equal-energy principle.

This advantage derives from two considerations, one a matter of physical principle and the other of instrumentation and engineering. Considering the second point, standard equipment is readily available from acoustical instrument manufacturers for making the necessary measurements of noise immission level in variable or intermittent noise climates. It is already possible to operate such equipment automatically and unattended in order to obtain reliable samples over long periods of time and, although at present this equipment is of a transportable rather than a portable kind, development in miniaturised electronics suggest that a truly portable device to perform the equivalent function is within reach. In essence it needs only to be a limited-range sound level meter with a straightforward integrating device instead of a visual meter at the output. It would thus be a simpler object than some types of "dose-meter" that have been proposed which work on a variety of rather complicated non-linear principles. The other advantage alluded to is that energy is the only physical quantity that is in its own nature cumulative when different sources superimpose their effects at a receiving point, in this case the ear. This permits a system of noise control for hearing conservation purposes to be evolved which, as one of us has already demonstrated in a study related to a major airport, is adaptable to flexible and changing work situations in highly complex patterns of noise sources without resort to personal dose-meters, the use of which would raise difficult problems of monitoring and maintenance if employed on a big scale. On this scheme, an individual's noise immission for a typical day is arrived at by combining a work study, to determine his pattern of movements and work positions, with a set of component noise immission values. The latter are classified by the source giving rise to them with simple adjustments for distance, and are determined once-for-all by physical measurement in advance of the operation of the scheme. The resulting total noise immission is equal to the value which would be registered by a portable integrating device if carried by the individual concerned. The accuracy attainable by this method is within 3 or 4 decibels. On the equal-energy principle, and only in these circumstances, can independent contributions be summed and the results of direct measurement and indirect assessment as outlined become compatible. With these advantages, we feel that the evidence against the principle would need to be more substantial and persuasive than it in fact is to outweigh them, and accordingly we recommend that, despite its possible—even probable

—over-protection in cases of marked intermittency, an equal-energy solution should be accepted for general purposes. This means that in a given period, which may be taken according to convenience as a day or a working week, only a certain maximum energy is permissible. This limit can be set at a variety of levels according to the ultimate risk judged to be acceptable, and we suggest that it should not be set higher than 90 dB(A) for a normal continuous daily exposure which is likely to persist for many years. This implies that each halving of the duration from 8 hours downwards may permit an increase of 3 dB(A), with over-riding conditions that no unprotected ear shall ever be exposed to a sound pressure level of 135 dB or more, and that the body as a whole shall never be exposed to a sound pressure level of 150 dB or more.

In recent years, both of us working independently on the preparation of various publications have advocated modified rules which constitute a kind of *via media* between the two alternatives outlined above, the essence of this adjustment being to assume a slightly more permissive noise level compared to the continuous 8 hour exposure according to the total duration of occurrence of the noise within a day. Such a scheme has also featured in successive drafts prepared under the authority of the International Organisation for Standardisation (ISO), but not in the latest version which relies entirely on the equal-energy principle. International discussion on this document, however, has not been finalised and we are unable to forecast the outcome at this moment. This type of modification is a compromise solution, being more permissive than the equal-energy principle but less permissive than the equinocivity principle. Like the equal-energy concept it ignores the element of recovery during periods of relative quiet. The attraction of this proposal in overcoming the possible over-conservatism of equal-energy is mitigated by its employment of a table of numbers representing the permitted noise level increase, based on TTS, so that its validity ultimately rests on the equivalence of the TTS/PTS relation for variable durations of exposure. Given these uncertainties, in advocating the unmodified equal-energy principle as we now do, we recognise that it is unwise to adopt a position that is too rigid in the light of advancing knowledge.

A further problem that remains is that of impulsive noise. This problem is not eased by the absence of a generally recognised or standardised method of measurement, though we note with satisfaction that this question is now under study by a Working Group

of the International Electrotechnical Commission (IEC). Recent proposals have been published that cover gunfire noise, but these are not really applicable to the types of impulsive industrial noise with which we are concerned. We did encounter noise with strong impulsive components, and in fact devoted much effort in an attempt to accommodate them into the survey. We felt obliged to exclude these noises from our present systematic examination, but there is little doubt that processes consisting of hammering are particularly damaging and should be treated with much caution, as obvious auditory hazards. In this field, study should be continued to attempt to achieve an acceptable method of measurement of these noises for the purpose of assessing the risk to hearing.

Finally, the status of the pure tone remains vague. Noise specifications for describing risk to hearing have in the past tended to ascribe to pure tones greater damaging effects than to broad-band noise. Noise consisting of, or containing, conspicuous pure tones is not very common, and we have no specific instance of it in our records. This stimulus would require to be defined acoustically in specific terms. In connection with the rating of noises for annoyance it is usually considered that a pure tone is present if it is audible, though the incorporation of this idea into acoustical prescriptions is proving to be very difficult. As regards risk of hearing damage, we believe that this criterion will prove not to be relevant; more probably the tonal component in the spectrum would have to be the dominant one for the effects to be markedly different from those which would be predicted from our diagrams on the basis of sound level A. In the meantime we are unable to provide specific recommendations on the hazards of pure tones.

Practical aspects of audiometry

The prospective and serial studies provided information of prime importance for the consideration of any systematic scheme of periodical monitoring of hearing in industry. From previous experience we had anticipated that the variability which is accepted as inevitable in pure-tone air-conduction audiometry, and which is not a serious drawback in clinical situations when the changes are appreciable, would present no serious obstacle in discerning average trends. However, this limitation operates more seriously in the individual case: the random changes may obscure the real changes unless considerable deterioration occurs. The result is that, in audiometry

in industry, which could well attain lesser levels of accuracy than our own, useful diagnostic trends might be undiscerned in the clutter of random variation of hearing levels. These effects are well understood and have been studied in detail. They are inseparable from the technique of audiometry as used, but improvement must be obtained if industrial audiometry is to play its part fully as a tool of preventive medicine.

The expedients immediately available to improve audiometry and the factors which could with advantage be studied further can profitably be considered here.

First, even now, substantial improvements in accuracy are available by means of repeat audiograms. In theory, the average of the hearing levels at a particular frequency measured on four occasions would depart from the true value by about half as much as would a single observation of hearing level at that frequency. As a practical measure we would strongly advocate that where pre-employment audiograms are being taken, they should be performed at least three times, preferably not at one sitting, and the mean at each frequency taken as the definitive value of hearing level. Similarly, when monitoring audiometry, say at yearly intervals, is being conducted, average values of three audiograms are the minimum on which reliance should be placed. This is a disconcerting conclusion, but it is inevitable in the light of our data, and is supported by reputable opinion elsewhere.

Even with these precautions, it must be accepted that, in routine monitoring audiometry, if deterioration is progressing at a rate determined by ageing alone (i.e. that deterioration due to noise is being prevented, which is the ultimate objective of such procedures) nearly one half of the subjects would show apparent improvements in hearing on successive occasions due to random error. Moreover, at middle frequencies, such apparent improvements would be about 5 dB for one in twenty persons. Conversely the same proportion could show deteriorations of about the same amount, and yet neither group need have changed at all in reality. On the basis of one audiogram these illusory results could be spread over a range of $\pm$ 8 dB.

Experience has suggested to us that minor improvements in self-recording audiometry could possibly be secured by simple modifications of technique. Thus the order of presentation of the test tones could be changed to make the task of the subject easier. The order in the Rudmose audiometer (which we would advocate for industrial

use, preferably with the tone-interruption facility) should be as stated in Appendix 16.

Looking towards other improvements in audiometry, the evoked response technique comes to mind. This holds considerable promise, particularly in controlling the psychological element in the subject's attitude. At the present time, however, its degree of precision offers no improvement and its complexity and unfamiliarity rather exclude it from immediate general use in the industrial context.

Assessment of susceptibility to occupational hearing loss

Of the numerous tests for susceptibility to TTS, and so, by implication, to PTS, most have used some kind of administered test with an arbitrary sound stimulus. Informed opinion has quite recently come to the conclusion, on grounds of the complexity of the relations between stimulus and the resulting TTS, that such tests are less likely to be fruitful than one based on the actual noise to which the subject will subsequently be occupationally exposed. For various reasons, this is the stimulus which we have used, and this approach has shown some promise.

Our approach included trials of various frequency combinations on which we based our indices of susceptibility to TTS and PTS. It turned out that of these, one combination, and by no means the most obvious, was markedly superior in illustrating an association between the two effects. The reason for this remains obscure, and provides a basis for speculation and possibly further investigation of its physiological implications. Taking advantage of this particular frequency combination, the development of a test for susceptibility to PTS follows a logical course. However, in pursuing this course, we find that whilst the construction of such a test is quite straightforward, the various sources of error conspire to blunt the edge of this prognostic weapon. The result is that the final critical value of TTS indicating a predetermined level of risk, becomes a range of values sufficiently great as seriously to undermine, for the moment, the value of the test as an everyday procedure.

Improvements in audiometry and in the technique of the test may well clarify the outcome. Even now, if the pre-exposure hearing level could be established with less uncertainty by the recognised expedient of averaging several measurements, it should be possible to distinguish between the susceptibilities of those above and below the upper

and lower quartiles of the population, respectively. Further work on this subject would appear to be well justified, and it could be programmed considerably more easily and efficiently in the light of the work already done.

Interpretation of audiograms

Although not in our terms of reference, and consequently virtually untouched by this investigation, one step of fundamental importance should be mentioned here. This concerns the translation of pure-tone audiometric hearing levels into terms of social disability. Obviously such a step is needed in the consideration of any scale of compensation for disability due to hearing loss.

In such considerations, a fundamental principle arises at the outset. This concerns the basis, in terms of hearing loss, on which a quantitative index of compensable disability should reside. On the one hand, the view might be taken that the only quantity relevant to compensation is that component of the hearing level specifically attributable to the effects of noise. The other view is based on the consideration that the deterioration due to noise, in the presence of age and other detrimental factors not necessarily in themselves capable of elevating the hearing level to the extent of a handicap, may precipitate such a condition. In the light of our somewhat refined and selective data, and of other data where entire working populations containing ears impaired by other factors in addition to noise have been included, it can be shown that these factors may conspire to produce a much larger percentage at risk than does noise alone. This situation is therefore not to be regarded as uncommon, and in the circumstances it is difficult to escape the conclusion that the second viewpoint enunciated above is the just one.

The actual translation of hearing measurements to degrees of disability is usually approached through the concept of preservation of speech perception, although it is obvious that a more liberal view would aim at a wider retention of auditory faculty. The position of pure-tone air-conduction audiometry and of speech audiometry is relevant in this context. There is a generous literature concerning the relationship between these two types of measure, but this only transfers the core of the problem to the interpretation of speech audiometry as a numerical index of handicap. Thus the attractions of the relatively simpler index provided by pure-tone hearing

levels justify attempts to quantify disability on this basis, at least initially. Working codes have been proposed for this purpose, and appear to serve reasonably well in many cases. However, agreement has not been achieved on the best combination of audiometric frequencies, and work is still in progress in an attempt to extend the usefulness of this technique.

In essence, the object of this entire investigation has been to provide the means of logical decision-taking, either on the risk inherent in a given noise situation for an exposed population or, so far as is possible, by providing prognostic indications to limit the risk for a given individual. The foregoing will have made it clear that, at present, a precise assessment of the effects of a specific noise exposure is only possible on a population basis, and then only with the proviso that aural pathology is effectively absent. However, in any unselected population the effects of a variety of agents must be added to the basic effects of increasing age and of noise. To give the reader some grasp of the quantitative implications, numerical illustrations may be helpful.

Starting at the hypothetical circumstances of least complication, we have seen that hearing deterioration is progressive with advancing age, and the attainment of a specific hearing level at a given age can be identified with a particular percentage of the population. If the hearing level were to be elevated by noise in a young population for which age effects were insignificant, some other percentage would attain this level. When age and noise operate together, the hearing level can be taken to be the sum of the two components. It is a peculiarity of the statistical distributions that the percentage of the population exceeding the specified hearing level is then greater than the sum of the above two percentages, until the point is reached when the involvement by either or both of the factors approaches totality. Similar considerations apply when a third factor, that of pathology, is introduced. To illustrate this, we will take for convenience a critical level corresponding to minimal disability for speech perception of 25 dB for the mean of the hearing levels at 0.5, 1 and 2 kHz (as advocated by the American Academy of Ophthalmology and Otolaryngology).

Assuming a population free from aural pathology at age 18 years, by the time they are aged 33 years a negligible proportion (theoretically less than 0·01 %) will have attained the critical level due to age alone. Had they been exposed occupationally to a continuous

daily noise of 95 dB(A), the critical level would have been exceeded by 4%. Thus the risk, as we define it in Appendix 1, would be assessed at 4%. If our hypothetical 33-year old population, instead of noise exposure, had suffered a median conductive hearing loss of some 20 dB (see Appendix 14), the percentage above the critical level would be 30%. If this group had also been exposed to the noise, no less than 58% would have exceeded the critical level. Thus the concatenation of these several causes produces a dramatic increase, to 28%, of the proportion of persons precipitated into the category of disability by exposure to the noise. Obviously, in a real situation, the proportion so affected must be expected to lie at some value intermediate between the 4% and the 28%. In a large study of an unselected American working population, such an intermediate value, namely 23%, was in fact found.

Methods of restricting noise exposure

We have already discussed the benefits of the elective situation created by our treatment, which permits flexibility in the setting of criteria and noise exposure limits. This facilitation of procedure should not, however, be allowed to obscure the primary need to contrive a working environment which is acoustically acceptable as it stands, without restriction of time or place or resort to special measures. Fundamentally, this means reduction of noise at source. Unfortunately, machinery, processes and equipment frequently bear little evidence of having been designed in this spirit, and vigilance must be exercised to guard against the production of new equipment giving higher noise levels than that which it supersedes.

Where unavoidable situations of potentially excessive noise exposure exist, the options available are 1) a reduction of duration, with or without 2) the use of ear protection. In the case of the latter, various devices of known sound reducing properties are available, and collected information is published in existing codes of practice such as that issued in this country by the Safety Services Organisation of the Ministry of Technology. The efficacy of all such devices depends not only on their intrinsic design but also on the frequency characteristics of the noise, and to take the best advantage of the protection they offer, an octave band analysis of the sound is necessary. Calculations can then be performed in order to determine the attenuation, in dB (A), of a particular ear protector in a particular noise. It must be

remembered, however, that for best results considerable knowledge and discretion must be applied to the choice, individual fitting and subsequent supervision of the protection. In addition, experience has shown that in moderate, yet harmful noise levels, there may be a marked aversion to the use of ear protectors which needs to be countered by explanation, persuasion and precept.

6
Concluding remarks and summary

As we near the end of this report, it is appropriate to return again to the point at which we began: the terms of reference. These we have interpreted as a request for a scientific investigation and appraisal of the factors relating noise to hearing loss in the industrial situation. The natural outcome of such an investigation would be a comprehensive and rigid formulation of regulations governing the control of noise and its effects in industry. We did not, in fact, have a brief for the production of such draft regulations, and in any event they imply broad questions of legislation which are clearly outside our province. Nevertheless, in the report, in its appendices and in the foregoing chapter in particular, there is virtually all the material from which a code of practice could easily and quickly be assembled in any particular format regarded as administratively suitable.

Finally, implied in our brief was the acquisition of the greatest amount of information relevant to noise and the resultant hearing loss in industry, consistent with a time-limited project. The wide scope of the project was only made possible by the admirable support which we received from the Ministries concerned and from the Factory Inspectorate in all the areas we visited, as well as from medical officers and from management, trade union and shop floor levels in industry. On behalf of all of us who participated in the work, we wish to offer our thanks for all the help which we received, not least to the subjects whose voluntary co-operation provided one of the two basic ingredients of the data.

Summary

(1) The effects of occupational exposure to steady noise on otherwise normal ears have been studied, together with a control population, by prospective, serial and retrospective methods. The results are broadly concordant.

(2) From the results has evolved a system of predicting, as a statistical distribution in an exposed population, the hearing

deteriorations to be expected from specified exposures within a wide range of occupational noises. The use of ear protection can be allowed for.

(3) Noise exposure can be described by a single number, based on dB(A) and time on an energy basis, so that the effects of complex exposures can be assessed. Conversely, specification of acceptable levels of exposure is greatly facilitated.

(4) The variability inherent in conventional pure-tone air-conduction audiometry, even of the highest standards, is shown to impose limitations on industrial audiometry; precautions to minimise these are discussed.

(5) Susceptibility to temporary threshold shift and to hearing deterioration attributable to occupational noise exposure have been shown to be associated. However, largely for the reason given in item 4, a practical prognostic test for susceptibility to occupational hearing loss has not yet been attained, although the form it might take is clear.

(6) It has not been possible to acquire data for daily exposures of duration less than a nominal 8 hours. In general, an equal-energy basis is advocated for such cases at present, on grounds of simplicity, safety and convenience.

(7) A small-scale study of ears impaired by disease and other detrimental factors, as well as by noise, illustrates how some degree of separate assessment of these components is possible. Such simultaneous impairments may greatly inflate the proportion of persons handicapped by noise-induced hearing loss.

(8) Our results comprise the necessary material for a formal code of practice for the preservation of hearing in industry.

Appendix 1
Glossary of technical terms

1. Acoustical and audiological terms

ARTIFICIAL EAR:
a device for loading an earphone with an acoustic impedance which simulates that of an average ear; used for measuring the sound pressure developed.

AUDIOGRAM:
(pure-tone air-conduction audiogram) a chart or table relating hearing level for pure tones to frequency.

AUDIOMETER:
an instrument for measuring hearing acuity.

AUDIOMETRIC REFERENCE ZERO:
a declared value, at a particular frequency, of the threshold of hearing for normal persons within a given age range, normally 18 to 25 years.
Note This Report makes use of the reference zero as specified in British Standard BS 2497:1954. It should be noted that there has recently been a revision (BS 2497 Part I:1968) bringing the former standard into line with ISO Recommendation R389. The difference is small, see Appendix 16.

BAND PRESSURE LEVEL:
the sound pressure level of the sound energy within a specified frequency band.

DEAFNESS:
in this text, a condition of hearing impairment recognised by the patient or other people as such.

HEARING LEVEL:
a measured threshold of hearing, expressed in decibels relative to a specified standard of normal hearing.

HEARING LOSS:
the symptom of reduced auditory sensitivity, synonymous with auditory impairment, when a specific cause can be ascribed. Also used, in a general sense, to describe the process of losing auditory sensitivity.

(1) Conductive hearing loss. A hearing loss originating in the conductive mechanism of the ear.
(2) Sensorineural hearing loss. A hearing loss originating in the cochlea or the fibres of the auditory nerve.
(3) Noise-induced hearing loss. A sensorineural hearing loss attributable to the effects of noise.

MASKING:
the process by which the threshold of hearing of one sound is raised due to the presence of another.

MASS LAW:
the approximately linear relationship between the sound insulation of a partition, expressed in decibels, and the logarithm of its weight per unit area.

NOISE EXPOSURE:
a generic term signifying the total acoustic stimulus applied to the ear over a period of time.

NOISE IMMISSION:
an index of the total noise energy incident on the ear over a specified period of time.

NOISE IMMISSION LEVEL (NIL):
the A-weighted noise immission, expressed in decibels relative to a specified datum (see under E, Appendix 2).

NOISE RATING CURVES:
an agreed set of empirical curves relating octave band pressure level to the centre frequency of the octave bands, each of which is characterised by a "noise rating" (NR), which is numerically equal to the sound pressure level at the intersection with the ordinate at 1000 Hz. The noise rating of a given noise is found by plotting the octave band spectrum on the same diagram and selecting the highest noise rating curve to which the spectrum is tangent.

PERMANENT THRESHOLD SHIFT (PTS):
the component of theshold shift which shows no progressive reduction with the passage of time when the apparent cause has been removed.

PRESBYCUSIS:
hearing loss mainly for high tones due to advancing age.

PRESUMED NOISE-INDUCED HEARING LOSS:
the component of a measured hearing level attributable to noise (see under H, Appendix 2).

PROSPECTIVE STUDY:
the form of serial study in which the first observation of hearing level occurs before any occupational noise exposure has been sustained.

RETROSPECTIVE STUDY (CROSS-SECTIONAL STUDY):
the observation of hearing levels of persons who have been exposed to known noises for known periods of time.

RISK:
the percentage of persons who, as a result of exposure to a specified noise immission level, may be expected to sustain a noise-induced hearing loss equal to or greater than a defined value.

SERIAL STUDY (LONGITUDINAL STUDY):
the observation of the hearing level of an individual at successive intervals of time.

SOUND LEVEL:
a weighted value of the sound pressure level as determined by a sound level meter.

SOUND LEVEL METER:
an instrument for measuring a frequency-weighted sound pressure level and having a declared performance in respect of its speed of response. Measurements are conventionally made with sound level meters conforming to weighting curve A and expressed in decibels, dB(A).

SOUND PRESSURE:
the alternating component of the pressure at a point in a sound field. The unit is the Newton per square metre (N/m^2).

SOUND PRESSURE LEVEL:
the sound pressure level of a sound, in decibels, is equal to 20 times the logarithm to the base 10 of the ratio of the RMS sound pressure to the reference sound pressure. For sound in air, the reference sound pressure is taken to be 2×10^{-5} N/m^2.

Note RMS denotes root mean square, i.e. the square root of the mean value of the squares of the instantaneous values of the sound pressure.

SPECTRUM:
a representation of the distribution of energy with respect to frequency.

(1) Octave band spectrum: the ensemble of octave band pressure levels comprising a sound. The audible spectrum is conventionally taken to embrace eight octaves.
(2) $\frac{1}{3}$-octave band spectrum: the ensemble of band pressure levels in bands $\frac{1}{3}$-octave wide comprising a sound.

TEMPORARY THRESHOLD SHIFT (TTS):
the component of threshold shift which shows progressive reduction with the passage of time when the apparent cause has been removed.

THRESHOLD OF HEARING:
of a continuous sound, the minimum RMS value of the sound pressure which excites the sensation of hearing.

TINNITUS:
a subjective sense of "noises in the head" or "ringing in the ears" for which there is no observable external cause.

TREND CURVES:
a set of curves describing the central tendency, and sometimes the dispersion, of the growth of PTS with time.

WEIGHTING CURVE:
a curve describing the frequency response of a sound level meter.

Curves A, B and C are defined in publications of the International Electrotechnical Commission (123 and 179) and in British Standard BS 4197:1967. A recommendation for a curve D is in course of preparation.

Note Curve C represents a nearly flat frequency response; the other curves have various degrees of low-frequency suppression.

WEIGHTING NETWORK:
an electrical network designed to be incorporated in a sound level meter such that the latter conforms to a specified weighting curve.

4 KHZ DIP:
(4 kc/s dip)
(4 kc/s notch)
the depression in the audiogram in the region 3 to 6 kHz associated with noise exposure.

2. Statistical terms

CENTRAL TENDENCY:
of a range of values of a variable x. The general position of the distribution of the values indicated by the following measures:

(1) arithmetic mean (average); the sum of all the values divided by their number, denoted by $\bar{x} = (\Sigma x)/n$.
(2) median; the value occupying the central position when the values are arranged in sequence from the least to the greatest.
(3) mode; the most commonly occurring value of x.

CORRELATION:
a procedure for investigating the degree of association between two (or more) characteristics of a population.

CORRELATION COEFFICIENT:
(product-moment correlation coefficient) a numerical indication of the degree of association between two characteristics of a population, x and y. Complete dependence of one characteristic on the other yields unity; no dependence, zero. It may be positive, for direct relations, or negative, for inverse relations. The value is given by

$$r = \frac{\Sigma\,(x - \bar{x})\,.\,(y - \bar{y})}{\{\Sigma\,(x - \bar{x})^2\,.\,\Sigma\,(y - \bar{y})^2\}^{\frac{1}{2}}}$$

DEGREES OF FREEDOM (DF):
the effective number of independent values of a variable, equal to the actual number n minus the number of constraints. In calculating a mean, DF = n; in calculating the standard deviation of a sample, DF = n − 1; in calculating a correlation coefficient, DF = n − 2.

DISPERSION:
the spread of values of a variable about the mean or median.

DISTRIBUTION:
the manner in which values in a sample or a population are distributed about the arithmetic mean. Various types and descriptions of distributions are recognised.

(1) Normal (Gaussian) distribution; a distribution commonly found in biological systems, in which the mean, median and mode coincide at the apex of a symmetrical bell-shaped curve of frequency of occurrence against magnitude of the item in a series.
(2) Cumulative distribution; a presentation in which the variable is plotted horizontally with the percentage of occurrence of all values less than the abcsissa plotted vertically. On a suitable graph paper, the points will fall upon a straight line if the distribution is Gaussian.
(3) Centile; a unit for defining the position in a series of values arranged in sequence from least to greatest, whereby each division is 1 % of the total.
(4) Decile; 10 centiles, usually used to designate the 10th and 90th centiles.
(5) Quartile; 2·5 deciles, normally restricted to describing the 25th and 75th centiles.
(6) Skewness; asymmetry of a distribution.
(7) Kurtosis; symmetrical deviation from the Gaussian distribution. An abnormally peaked distribution is called leptokurtic; an abnormally flattened one platykurtic.

LINEAR REGRESSION:
of one characteristic on another. A description of the manner in which one characteristic varies with respect to another, as described by a straight line fitted to the data by the method of least squares, the deviations being measured in the direction of the first characteristic.

(1) Regression coefficient; the numerical value of the change that, according to the slope of the regression line, takes place in one characteristic for unit change in the other.

LEAST SQUARES:
a criterion to establish the curve or straight line of best fit to points on a graph.

POPULATION:
the ensemble of values of a variable from which a sample is drawn.

PROBABILITY (P):
see Statistical Significance.

RANDOM ERROR:
see Residual Variance.

RANK:
the ordinal number of an item in a series which is arranged in sequence from the least to the greatest value of the items.

REGRESSION:
a generalisation of linear regression (q.v.) when two characteristics are related by a curve.

RESIDUAL VARIANCE:
in general, the unexplained part of the total variance. In regressions, the mean squared deviation from the regression line, sometimes referred to loosely as regression variance.

STATISTICAL SIGNIFICANCE:
an expression of the degree of confidence which can be attached to the occurrence of an event. It is normally given a numerical value by stating the proportion of times on which the event could occur by chance. The conventional level of 'significance' is that the occurrence could only arise by chance in 5% of cases; commonly designated probability $P = 0{\cdot}05$.

SCATTER DIAGRAM:
a graphical presentation, for example relating two series of variables, in which a separate point indicates each pair of corresponding values.

STANDARD DEVIATION:

a numerical indication of the scatter of values of a variable around their mean (symbol σ). Specifically, it is the square root of the mean squared deviation, given by $\sigma = \{\Sigma(x-\bar{x})^2/n\}^{\frac{1}{2}}$. In a normal distribution, a range of 2 standard deviations on each side of the mean will include 95·45% of all the values, and 3 standard deviations on each side of the mean, 99·73%.

Note When the standard deviation is determined from a sample of values and not from the parent population (which is frequently unknown), the denominator within the square root should be taken as $n - 1$, due to fact that one degree of freedom out of the total n is used to estimate the mean value $\bar{x}$.

STANDARD ERROR:

of the mean of a sample. The standard error is found by dividing the standard deviation of the items in the sample by the square root of their number. The mean of the population from which the sample was obtained is not likely to differ from the sample mean by more than plus or minus twice the standard error.

VARIANCE:

the mean squared deviation of the values of a variable from their mean. The square of the standard deviation.

Appendix 2

List of symbols used

a A constant

A A proportionality constant

b A constant; a regression coefficient

c A constant; a second-order regression coefficient

C_i A frequency-dependent coefficient for the presbycutic component of hearing loss. i denotes the audiometric frequency.

D (general symbol) The deviation between an audiometric value for an individual and the mean, or median, for a group.

- D_P An individual age-corrected hearing level expressed relative to the predicted median value for persons of the same age and with the same NIL.
- D'_T An individual value of TTS expressed relative to the mean value for a group of persons within a specified band of NIL or of L_{A2}.
- D_T The value of D'_T after correction for hearing level.
- D_S An individual persistent threshold shift expressed relative to the predicted median threshold shift for persons with the same initial and final values of NIL.

E (general symbol) A measure of noise energy, expressed in decibels.

- E_A A-weighted noise immission level (NIL), equal to $L_A + 10 \log (T/T_O)$.
- E_{A2} Another value of the noise immission level, defined by $L_{A2} + 10 \log (T/T_O)$.
- E' Frequency-normalised noise immission level given by $E_{A2} + \Delta E_{A2}$, where the normalising constant ΔE_{A2} depends on the audiometric frequency and is taken to be zero at 4 kHz.
- E_O A constant in the equation for H.

H (general symbol) A pure-tone audiometric value, in decibels.

- H'_O A hearing level relative to British Standard zero as specified in BS 2497:1954.
- H_O An age-corrected value of H'_O.
- H' A hearing level expressed relative to non-exposed controls in the age group 18 to 25.

H Age-corrected hearing level relative to controls in the age group 18 to 25. Assumed to be equal to the difference between the hearing level and that of non-exposed controls of the corresponding age. This quantity is also termed "presumed noise-induced hearing loss" in appropriate cases.

H_∞ The maximum attainable hearing level.

k The duration exponent in the general formula for noise exposure index $L + k \log (T/T_O)$.

K A constant.

L (general symbol) Sound pressure level of a noise, in dB re 2×10^{-5} N/m^2.

L_{63}, L_{125} . . . L_{8000} Octave band sound pressure levels. The suffix denotes the geometric mean frequency of the band.

L_A, L_B Weighted sound pressure levels, in dB(A), dB(B).

$L_{A2} \ldots L_{A50}$ The value of L_A exceeded for 2 . . . 50% of the time.

m A multiplying factor applied to the presbycusis correction.

n Number of subjects, etc. incorporated in a statistic.

N Age, in years.

p A centile of noise-exposed population, reckoned from the most susceptible (0%) to the most resistant (100%).

P Probability, in tests of statistical significance.

r Product-moment correlation coefficient.

s Impairment rate index given by $\Delta_{LR}/\log\{1 + (\Delta T/T)\}$

S A measure of the general slope of the octave band spectrum. The value of S is negative for rising spectra, positive for falling spectra.

S_1 The value of S defined by $\frac{1}{2}(L_{250} + L_{500} - L_{2000} - L_{4000})$.

S_2 The value of S defined by $\frac{1}{3}(L_{250} + L_{500} + L_{1000}) - \frac{1}{2}(L_{2000} + L_{4000})$.

S^2 Mean square deviation about a curve of best fit.

T Exposure duration reckoned on the basis of 8 hours per day, 5 days per week. The unit is 1 calendar month or year.

T_O A reference duration, equal to the unit (month or year) in which T is reckoned.

T_1 The value of T at the time of first audiometric test.

TTS The magnitude in decibels, of a temporary threshold shift.

Note The same symbol is used as an abbreviation when no numerical value is attached.

u A parameter in the equation for H, related to the value of p through the properties of the Gaussian distribution.

u^2 A component of variance.

v^2 A component of variance.

X The calculated value, for the median person, of the threshold shift $\Delta_{\overline{346}}$ expressed relative to the corresponding value $\Delta_{\overline{12}}$.

Y An observed value of the relative threshold shift corresponding to X.

Δ An increment of hearing level, measured under corresponding conditions, i.e. a permanent threshold shift.

ΔT The time interval between audiometric tests, reckoned in the same units as T_1.

λ_i A frequency-dependent parameter in the equation for H, equal to $E_O - \Delta E_A$. i denotes the audiometric frequency.

μ A constant in the equation for H.

σ (general symbol) Standard deviation.

σ^2 (general symbol) Variance.

$\sigma_O{}^2$ Error variance.

$\sigma_S{}^2$ Intersubject variance.

Σ Summation sign.

Suffix notation

L A value related to the left ear.

R A value related to the right ear.

LR The average of values related to the left and right ear; in correlation, left against right.

·5, 1, 2, 3, 4, 6 Audiometric frequency in kHz.

$\overline{12}$, $\overline{23}$, $\overline{346}$ The average of a value over the frequencies 1 & 2, 2 & 3, 3, 4 & 6 kHz etc.

Note The suffixes for left and right are sometimes combined with those for frequencies or frequency averages, thus $\Delta_{LR\,\overline{346}}$.

Appendix 3
Personnel concerned in the investigation

The Joint Working Group 1962-1965

The Joint Working Group was composed of representatives from both the National Physical Laboratory and the Medical Research Council, and operated under a joint chairmanship. The members comprised:

CO-CHAIRMEN

Professor W. Burns—Medical Research Council
Dr B. W. Robinson—National Physical Laboratory

MEMBERS

Medical Research Council
Dr P. J. Chapman
Dr T. S. Littler
Mr A. Tumarkin
Dr J. J. Knight
Dr A. S. Fairbairn
Air Commodore H. W. Penney (Administrative Officer)

National Physical Laboratory
Dr D. W. Robinson
Dr M. E. Delany (Secretary)
Mr W. C. T. Copeland

Medical Research Council Staff

Responsibility for the staffing for operating in the field was undertaken by Dr T. S. Littler of the Wernher Research Unit (Medical Research Council) from the commencement of the investigation until mid 1966, thereafter control was exercised on behalf of the Medical Research Council by Professor Burns through the Administrative Officer. The team, in charge of a physicist, contained an otologist together with two or more audiometricians and technicians.

The names of those who at various times participated are given below:

(a) PHYSICISTS (in charge of field team)
Dr J. J. Knight
Mr B. S. Webster
Dr J. C. Stead

(b) OTOLOGISTS

(i) *July 1963 — August 1964*
Mr W. Wipat
Mr M. Horowitz

(ii) *August 1964 — January 1966*
During this period arrangements were made mainly with Dr R. Hinchcliffe and Mr K. Ferris of the Institute of Laryngology and Otology, for the provision of otologists on a sessional basis.

(iii) *February 1966 — September 1967*
Dr Barbara E. Wood

In addition, Dr R. Hinchcliffe greatly assisted the work of reviewing the clinical status of the audiometric and otological data.

(c) ASSISTANTS

Mr M. C. Asher	Miss J. A. C. McKinlay
Mr A. D. Cheesman	Mr C. R. Millross
Mr M. Fisher	Mr R. Oldham
Miss D. H. Gilmore	Mr M. G. Prentice
Mr I. D. Griffiths	Mr A. N. Ramsey
Miss M. I. Johnson	Mr S. D. G. Stephens
Miss A. C. McDowell	Mr P. J. W. Venables

National Physical Laboratory Staff

Responsibility for the National Physical Laboratory participation was undertaken by Dr D. W. Robinson. The work is conveniently

divisible into three aspects, the names of those concerned at various times being as follows:

(a) Design of vehicles, maintenance of calibration
Mr W. C. T. Copeland
Mr L. S. Whittle
Mr E. G. Saunders
Assistant Mr A. C. Bartlett

(b) Field noise measurements
Mr W. C. T. Copeland
Mr E. G. Saunders
Mr P. D. Cobham
Assistants Mr R. C. Payne
Mr R. Cooper

(c) Data processing
Mr A. J. Burton (Division of Numerical and Applied Mathematics)
Miss Judith P. Cook
Miss Lynda A. Burdon

In addition Dr M. E. Delany carried out pilot studies designed to assist in the formulation of the definitive programme of hearing measurement,and also participated inthe formative stages of the data analysis. Advice on statistical theory was provided by Mr J. G. Hayes of the Division of Numerical and Applied Mathematics.

Appendix 4

The mobile audiometric laboratory*

by W. C. T. Copeland, L. S. Whittle and E. G. Saunders

Design considerations

It was decided that reasonable internal dimensions for the booths were about 1·2 m deep, 0·84 m wide and 1·8 m high. Considerations of weight distribution on whatever chassis was chosen, and of leaving adequate space for working and the passage of subjects and operators, largely dictated that the booths should be arranged in twos, side by side, at each end of the vehicle body.

The framework of the body had to be sufficiently strong to carry a fairly heavy outer skin, and also stiff enough to carry the booths which were supported top and bottom by anti-vibration mounts. Therefore the framework had to be reasonably thick. It was impracticable to achieve the required sound reduction exclusively in the booth construction, since this would necessitate a soft-suspension double construction unsuitable for the road and in any case it would occupy too much space. Following general principles of sound reduction by double enclosure it was therefore decided that the insulation given by the vehicle skin should be of the same order as that given by the booths. These considerations, together with the booth configuration adopted and the necessity to leave a small space between booths and walls, dictated that the body and the booth skins should have an approximately equal thickness of about 9 to 10 cm.

Weight is a primary consideration in achieving high insulation, but there are obvious limits in the case of a vehicle. However, the lowest audiometric frequency to be used normally was 500 Hz, which meant that the low frequency insulation requirements need not be too severe. From the logarithmic relation between weight and insulation of partitions, which applies at low frequencies even to non-homogeneous examples, it follows that relaxation of insulation by a few decibels results in a marked reduction of weight, and a figure of 10 to 11 tons was decided on as a reasonable compromise between the

*Adapted from the paper published by the same authors in J. Sound Vib. 1964, **1**, 388.

conflicting factors involved, and of this 3 tons or so would have to be allocated for chassis weight.

The choice of a petrol-engined four-wheeled $7\frac{1}{2}$ ton chassis was finally made after consideration of six-wheeled and articulated versions, partly by reason of lower initial cost and partly because the use of those more elaborate chassis did not appear to offer any marked advantages. The articulated vehicle, for example, would have been excessively high unless a drop-frame trailer was used and this, with the configuration of booths, would have meant wasted space forward.

Another major decision in design was to arrange for continuous air-conditioning of the booths and working area of the vehicle, which meant the installation of silenced ductwork.

Description of the vehicle

The overall length of 9·1 m was the maximum permitted for a four-wheeled commercial vehicle; the external width is 2·4 m and the height 3·6 m. The gross weight is $11\frac{1}{2}$ tons. The chassis used is a $7\frac{1}{2}$-ton Bedford KGL whose normal wheel-base of approximately 4·3 m was extended to 5·4 m by means of a commercial chassis extension (Baico). The sound-proofed part of the body is in effect a box approximately 7·2 m long by 2·4 m high, which is supported on chassis runners by anti-vibration mounts. To avoid the "box-on-wheels" look, the scuttle was modified to fit smoothly with a light-weight aluminium alloy cab which is faired into the remainder of the body to give a neat appearance. The external skin of the body is also carried downwards to form a skirt in which are fitted flush door-hatches giving access to spare wheel, cable locker, entry-steps, fan units, etc., which are all carried below the floor level.

An external view of the vehicle is given in Fig. 4.1. The hydraulic pump controlling the four-section jack-knife door is manually operated from either within the vehicle or the cab. The hatch-door below conceals captive pull-out aluminium steps with detachable handrail. The hatch-door below this gives access to a plenum fan unit, whose air intake is made via the louvres to be seen to the top left-hand side of the door, thus minimising the possibility of fumes being drawn into the vehicle. A corresponding hatch-door on the offside gives access to an extract fan unit. The hatch-door forward of the jack-knife door opens to the spare wheel, that at the rear opens

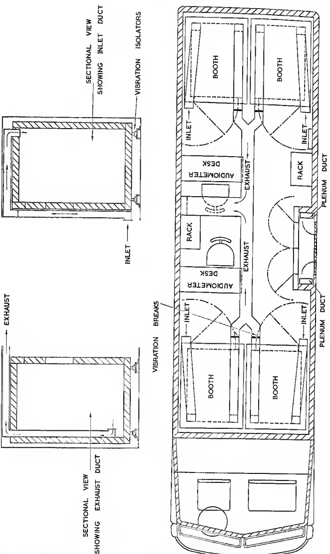
4.1 Exterior view of the vehicle.

to a cable locker, two 90 m lengths of mains supply cable being carried. Access to the engine is via the hatch-door under the rear cab window and a corresponding one on the offside. An emergency escape hatch is located in the body wall offside.

The interior lay-out of the vehicle is shown diagrammatically in Fig. 4.2 and a view taken from within a forward booth in Fig. 4.3. Each desk carries two audiometers and associated with each desk is an instrument rack carrying calibration and checking apparatus.

On the right of Fig. 4.3 can be seen the centre-closing sound lock door which provides most of the insulation over the entry area. The ducting at roof level is part of the extraction system from booths and body.

Lighting is given by three mains-operated fluorescent fittings in the roof and one in each booth, the double-glazed windows in the upper half of the sound-lock and jack-knife doors being provided more as a safety measure than a means of natural lighting. The ballast chokes, etc., for the lights are placed in the sound lock area so that ballast noise is inaudible in the booths. Emergency lighting is provided by two roof lights in the body, operated from the vehicle battery. These



4.2 Interior layout of the vehicle.

4.3 Interior view of the vehicle.

come into operation automatically if the mains supply fails or is disconnected.

All wiring to lights, mains points, fans, etc., is either buried in the vehicle walls or carried in plastic ducting under the floor. For convenience, the wiring between booths and audiometers is carried in surface-mounted $5 \times 2 \cdot 5$ cm metal ducting, the ducting being divided to keep the wiring to each booth separate to eliminate the possibility of cross-talk. Intercom sets permit communication between booths and desks and, incidentally, between both of these and the attendant caravan used as an examination and waiting room.

The floor lay-out required some ingenuity to achieve the optimum, bearing in mind door arcs, the requirement that access to booths and door be unimpeded as far as possible, and the convenience of the two operators in working and checking the audiometers.

Ventilation

The lay-out of the ventilation system is given in Fig. 4.2 and is partly visible in Fig. 4.3. Air is drawn through the high level intake via metal ducting to a fan/heater/filter unit located under the body below the jack-knife door and is discharged via another duct into the body of the vehicle at high level from the side of the sound lock. These two ducts are located within the sound lock. Extraction is made via the booths, a vertical duct connecting the extract fan unit located on the offside of the vehicle to a duct running along the centre line in the roof, which subdivides with flexible connections to the booths.

All ducting is lined with absorbing materials, and made of heavy gauge metal. The ducts on the booths and the vertical section leading to the extract fan are covered externally by a heavy lead-loaded plastic material to minimise noise transmission through the duct walls. Ventilation noise (see later) is inaudible in the booths.

The capacity of the fans is about $0 \cdot 06$ m^3/s maximum (with two alternate lower flow settings), giving about 25 air changes per hour in each booth. The heater fitted in the plenum fan unit is rated at 2 kW maximum (with two alternate lower settings), which was estimated to give a temperature rise of about 35°C in air inlet temperature and, including heat dissipated by the apparatus, an average air temperature of about 20°C in the vehicle body under normal winter conditions. Electric space heating was planned to augment the heat input as and when necessary.

Booths and vehicle body

The booths have internal dimensions of 1·2 m deep by 1·8 m high by 0·84 m wide, the walls being 10 cm thick. The booths were constructed to the required dimensions, together with their silenced air-ducts and the sound lock, by Industrial Acoustics Company Ltd. The total weight is about 860 kg for each booth, the superficial weight of the walls being about 73 kg/m^2 excluding framing. Each stands on six anti-vibration mounts, with one additional mount at the top between booth and vehicle roof to prevent gross lateral movement. The natural frequency of the suspension is about 10 Hz. This is a compromise between the ideal of an extremely soft suspension necessitating some form of locking mechanism for the booths when the vehicle is travelling and the extreme of a very stiff and therefore acoustically ineffective mounting.

The detailed design of the outer bodywork, framing and fittings and construction of the vehicle was carried out by Messrs. Bonallack of Basildon, Essex, who also installed the booths, sound lock and door provided by Industrial Acoustics Company Ltd., with whom they collaborated.

The walls and roof of the vehicle are constructed as follows:

(1) outer cladding of 16 S.W.G. anti-rust treated mild steel sheet,
(2) 5 cm thick rock-wool compressed to 3·8 cm,
(3) 1·3 cm thick plaster-board,
(4) 5 cm thick glass fibre compressed to 3·8 cm, and
(5) an inner cover of 22 S.W.G. perforated aluminium alloy sheet.

The total thickness is just over 9 cm and the superficial weight, excluding vehicle framing, is approximately 34 kg/m^2. Items (1), (2) and (3) are assembled on the pillar frames, the plaster-board being flexibly mounted on sponge rubber and soft sealing compound between the pillars. The sheets extend from floor to roof. Hardwood framing is used to support the perforated inner cover and this is supported from the vehicle frame pillars by rubber pads.

The floor construction is the same, except that (1) is of 20 S.W.G. aluminium alloy sheet and (5) is of 10 S.W.G. mild steel with a vinyl floor covering; it was not practicable to isolate inner and outer skins. The skin combination was designed to give as high as possible an increase in sound reduction compared to the mass-law value for a partition of the chosen weight over most of the frequency range,

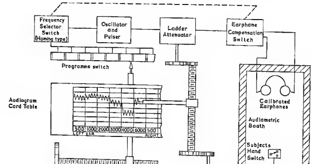
bearing in mind that a true floating partition is incompatible with the rigidity necessary for a mobile assembly.

At low frequencies the skin would be stiffness controlled, thus tending to give higher insulation than mass law. The weight and spacings of inner and outer skins give a resonant frequency of about 120 Hz, considerably damped by the absorbing materials. Above about 170 Hz, the insulation is again higher than mass law and rises sharply with frequency. The glass fibre lining is necessary to absorb sound inside the vehicle; the inner membrane of plaster-board may also contribute absorption at low frequencies.

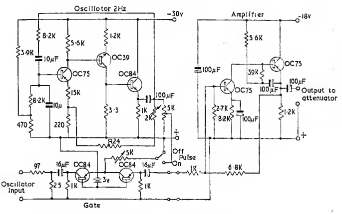
The sound lock door has the same construction as the booths, and the escape hatch the same as that of the walls, thus obviating weak points in the skin, adequate sealing around the edges having been specified.

Audiometric equipment

The basic equipment consists of four Rudmose type ARJ-4 self-recording audiometers which are installed in pairs in the consoles shown in the photograph, Fig. 4.3. These audiometers, shown schematically in Fig. 4.4, consist of an audio frequency oscillator, the output of which is fed by way of a motor driven attenuator, under



4.4 Schematic diagram of the self-recording audiometers.



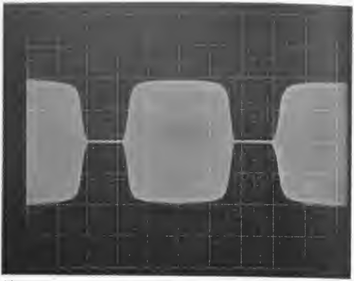
4.5 Circuit diagram of pulsing unit.

the control of the subject, to a pair of calibrated earphones worn by the subject which provide the sound stimulus. The intensity of the tone heard by the subject is either continuously increasing or decreasing, depending on the position of the hand switch. The frequency of the test tone is automatically changed at half-minute intervals, and when the left ear has been tested at the six frequencies 0·5, 1, 2, 3, 4 and 6 kHz the other ear is tested similarly. Thus an audiogram for both ears is provided in about six minutes.

Several modifications were made to the audiometers in order to meet the requirements of the project. The audiometers normally produce a continuous note; however, it was considered preferable to use interrupted tones. The pulse unit (Fig. 4.5) developed for the purpose provides these interrupted tones free from distortion at the onset and decay of the tone and free from clicks. Fig. 4·6 shows typical waveforms of the test tone; (a) represents the envelope of a pulse (duration about 300 msec) and (b) is an enlargement of the onset transient of the 1000 Hz pulsed tone.

Another modification is the use of the British Standard reference earphone, STC type 4026A, in place of those supplied, and the calibration of the audiometers to the British Standard (1), in place of the American data to which the apparatus was originally designed.

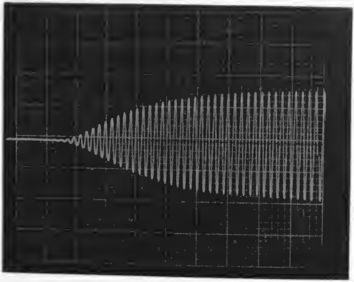
In normal routine audiometry, as practised in clinics and hospitals, the precision required is not too stringent and calibrations are rarely



(a)

(b)

4.6 Oscillograms of pulsed tone.
(a) envelope of pulsed audiometer tone.
(b) onset of 1000 Hz pulse.



made more than once a year. The British Standard on Audiometers (2) requires that the sound pressure produced by the earphone shall be within ± 5 dB of the indicated value. For the present purposes a much higher standard of accuracy was required. Accordingly the initial laboratory standardisation of the audiometers was performed to an accuracy of $\pm \frac{1}{2}$ dB. The monitoring equipment installed in the vehicle permitted convenient and frequent routine checks of the stability of the audiometers to the same accuracy and enabled adjustments to be made when necessary; permanent wiring between booths and consoles facilitated monitoring procedure.

The principal objective test of an audiometer is the measurement of the sound pressure produced in an artificial ear for specific settings of the attenuator. This must be done at each of the frequencies used, and with each earphone. These measurements were made daily. Any changes or faults were thus detected with minimum delay and the risk of rejection of valuable audiometric results reduced to negligible proportions. Further checks provided for are the values of the steps of the attenuators and of the frequencies of the test tones.

The apparatus, for the most part mounted on the two racks as shown in Fig. 4.3, consists of artificial ears, Brüel & Kjaer type 4151, in which the sound pressures set up by the earphones are measured by means of condenser microphones type 4132 with associated cathode followers type 2613. The electronic equipment associated with the artificial ears is the type 2137 frequency analyser, used in this case as a high-sensitivity frequency-selective valve voltmeter, calibrated to read sound pressure level directly. The choice of the type 4151 artificial ear for monitoring was governed by availability and operating convenience, but it should be distinguished from the British Standard artificial ear (3) used for the fundamental calibration. Digital frequency meters provide rapid measurements of the frequencies of the test tones to an accuracy of 1 Hz.

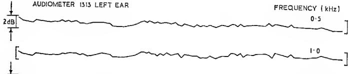
The duplication of the apparatus described has several advantages: calibrations can be carried out faster; one set of apparatus can be checked against the other; a failure in one set of equipment does not prevent calibrations from being made. Further, a range of auxiliary equipment was provided to facilitate servicing of the audiometers. This includes a Brüel & Kjaer beat frequency oscillator type 1034, a pistonphone type 4220 (for providing an absolute calibration of the microphones at one frequency) and an oscilloscope for observation of the pulsing characteristics.

The four audiometers remained remarkably stable in output throughout the entire period of the investigation. An example is illustrated in Fig. 4.7 in which, to accommodate the whole time scale on the abscissa, the lines shown connect points each of which represents the average calibration over a period of some two weeks.

Test of noise reduction

The sound insulation performance of the vehicle was assessed in two ways: firstly, by immersing the vehicle in a random noise field and, secondly, by directing sound at the near side of the vehicle in the open, warble tones being used in this case.

In the random field tests, the sound pressure levels in $\frac{1}{3}$-octave bands were measured (a) at fourteen points outside and (b) at three points inside the vehicle along the centre line. The test sound used was a band of noise one octave wide which embraced the particular $\frac{1}{3}$-octave under measurement. The noise reduction was taken to be the difference between the mean levels (a) and (b). The sound pressure level at the subject's head position in the booths (c) was also measured, the quantity (a) − (c) thus giving the overall noise reduction.



4.7 Calibration log of audiometer, serial no. 1313 over the years 1963–1969.

In the open-air tests the outside measurements were made close to the vehicle skin and 6 dB was subtracted from the mean level to estimate the free field level. Measurements were made as above inside the vehicle and the booths.

An assessment of the performance of the booths alone was made by placing loudspeakers inside the vehicle. A number of reservations must be made on the values obtained, however, since the absorbent lined interior of the vehicle prevents the setting up of a sufficiently diffuse field and it cannot be said that sound was uniformly incident over the whole of the surface of the booths because of their position.

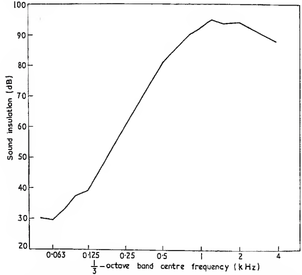
TABLE 4.1
Results of noise reduction tests (dB)

	Band centre frequency (Hz)						
	63	125	250	500	1000	2000	4000
Outside vehicle to inside booths							
Noise reduction I	31	41	58	83	97	96	88
	31	40	58	79	93	86	88
	30	38	58	77	87	95	87
	31	41	58	76	90	95	88
Mean	31	40	58	79	92	93	88
Noise reduction II	32	44	61	—	–	—	—
Mass law+:							
107 kg/m² (skin plus booths)	—	27	32	37	42	48	54
460 kg/m² (9 in brick)	—	35	41	47	54	62	69
Outside to inside of vehicle							
Noise reduction I	23	25	33	44	52	56	59
Noise reduction II	20	26	36	47	—	—	—
Mass law+: 34 kg/m²	—	22	26	31	35	39	44
Inside vehicle to inside booths							
Noise reduction III	20	25	37	49	54	57	57
	23	27	37	45	49	49	53
	19	22	38	50	54	60	62
	21	27	37	48	52	50	53
Mean	21	25	37	48	52	54	56
Mass law+: 73 kg/m²	—	25	30	35	40	45	51

I Random incidence on body.
II Sound incident on near side only; limitations of the apparatus available at the time precluded sufficiently accurate measurements at the higher frequencies.
III Loudspeakers in vehicle.
+ See reference (4).

This is probably in part the reason for the different sound pressure levels measured in the various booths. These measurements, apart from some confirmatory measurements in $\frac{1}{3}$-octaves, were made in octaves with centre frequencies based on the preferred series 63, 125, 250 . . . Hz. For simplicity the results are given in terms of octave band noise reductions in Table 4.1, together with sound reduction indices (interpolated from reference (4)) for single homogeneous partitions of the same superficial weight. The values are also shown in Fig. 4.8 (overall reduction in $\frac{1}{3}$-octaves) and in Fig. 4.9 (vehicle body and booths separately, in octave bands).

Listening inside the vehicle showed that the sound came more via the floor than the walls at frequencies around 200 Hz, perhaps due to the impracticability of isolating the inner and outer skins of the floor. The results obtained, however, show a considerable gain over simple mass-law figures at medium and high frequencies, which was the aim of the design.

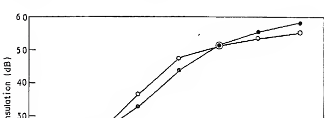


4.8 Total sound insulation, measured in $\frac{1}{3}$-octave bands (mean for four booths).

Descriptions and constructional details of other audiometric vehicles, together with noise reduction measurements made on them, are given in references (5) and (6). It should be noted that comparison with sound reduction indices based on the mass law is a rather arbitrary procedure. The nature of the interior (receiving side) obviously enters in, e.g. the amount of absorbent present, the transmitting area, and, in this case, the air stiffness provided by the volume of enclosures. In the case of the random noise tests, where the sound can be taken as incident roughly over the whole of the vehicle, instead of only upon the side facing a sound source, the noise reduction figures are likely to be less than the sound reduction indices of the constructions. Moreover, at low frequencies compound partitions show no sound reduction advantage over simple ones, so that a value even below the mass law might be expected.

Sound pressure levels in two of the booths due to the fans at maximum speed were measured, and are given in Table 4.2.

The values obtained show that fan noise would not intrude on audiometric measurements even for subjects with very sensitive hearing, e.g. 10 dB better than normal.



4.9 Sound insulation of vehicle body and of booths, measured separately in octave bands. Symbols: vehicle body, •; booths, o.

TABLE 4.2
Fan noise sound pressure levels in the booths

$\frac{1}{3}$-octave band centre frequency (Hz)	Sound pressure level (dB re 2×10^{-5} N/m^2)
31·5	29
40	26
50	29
63	33
80	28
100	24
125	18
160	9
200	< -2
250	< -2
500	< -2
1000	< -2

Permissible ambient noise levels

The level of noise in which the vehicle may be placed without affecting the accuracy of the audiometric measurements is determined by the five following factors.

(1) Overall sound attenuation from outside the vehicle to inside the booths.

(2) Audiometric test frequencies. The lowest frequency is the one most likely to be prejudiced by extraneous noise, and the calculations are therefore based primarily on 500 Hz.

(3) Threshold level to be measured. It has been assumed here that hearing levels appreciably lower than normal (British Standard) should be catered for, and for the sake of specificity the background noise limit has been calculated so as to introduce an error of no more than 1dB for a hearing level of -6 dB or no more than 2 dB for a hearing level of -10 dB, i.e., a hearing level of up to -12 dB relative to normal. The standard deviation associated with the normal threshold of hearing at middle frequencies (7) is about 6 dB, so that the criterion adopted is equivalent to saying that 3% of normal audiograms would be subject to the influence of the intruding noise by 2 dB or more, but then only if the noise level were continuous at the limiting level.

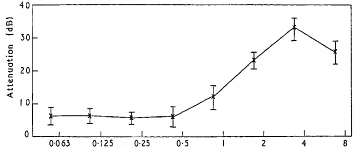
(4) Attenuation given by the headset. Since data for the 4026A earcap do not appear to have been published, a subjective experiment

with a team of eleven observers was run to determine the real-ear attenuation directly. A substantially uniform sound field was set up by means of loudspeakers fed from an octave-band noise generator in a sound-proof cabinet. The subject kept his head in a well-defined position while the binaural threshold was determined for each octave band, with and without the headset in position (the headset of course being unenergised). The mean value of the threshold shift with 95% confidence limits for the group is given in Fig. 4.10.

(5) Masking function. It is not necessary that the intruding noise should be inaudible to the subject undergoing the audiometric test, only that its level should be below that which masks the test tone at his threshold level. When the centre frequency of an intruding noise band is below that of the test tone, the noise will not mask the tone unless it is of greater level, and the greater the frequency separation, the greater the level of the noise that may be permitted before it

TABLE 4.3
Limiting levels in ⅓-octave bands for masking of a 500 Hz tone by a noise

Centre frequency of band (Hz)	50	63	80	100	125	160	200	250	315	400
Limiting level of noise band that will just not mask a 500 Hz tone (dB re threshold of 500 Hz tone)	48	44	39	35	31	27	23	18	12	5



4.10 Attenuation through earcap of the 4026A type earphone with 5N head-band force. The means for 11 subjects are shown with 95% confidence limits.

just masks the tone. For the present calculations, the function relating the band pressure level and centre frequency of masking noise to the tone it masks was taken from reference (8), where it is expressed in terms of masking noise bands $\frac{1}{3}$-octave wide. A conservative estimation has been made in order to offset the fact that the experimental data of reference (8) relate to the masking effect of individual noise bands, whereas the object is to set a noise spectrum limit on the assumption that all low frequency bands might exercise their effect collectively. Table 4.3 gives the level in $\frac{1}{3}$-octave bands of a noise which will just not mask a 500 Hz tone; it is expressed in decibels relative to the threshold for the tone. Similar tables may be constructed for test tones of other frequencies by reference to Zwicker's data.

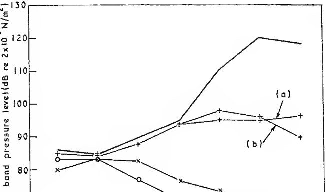
The calculation of limiting noise levels outside the vehicle now proceeds along the lines of the following example:

	Allowance (dB)	Net result dB re 2×10^{-5} N/m^2
Absolute normal threshold at 500 Hz (monaural telephone) from BS 2497		12
Allowance for negative hearing level	−12	0
Allowance for masking effect, noise band centred on 50 Hz	48	48
Allowance for headset attenuation	6·5	54·5
Allowance for vehicle attenuation	30	84·5
Hence permissible outside noise level in 50 Hz band		84·5
Similarly in 63 Hz band		80·0
and in 80 Hz band		78·5
Hence permitted outside noise level in octave band centred on 63 Hz (84·5, 80·0 and 78·5 combined)		86·5
Similarly, for the octave band centred on 125 Hz		84·5
and on 250 Hz		90·5

This procedure is valid up to and including the frequency of the lowest audiometric tone used (500 Hz); above this, so far as audiometric tests at 500 Hz are concerned, arbitrarily higher limits could be accepted, but when the tests at higher frequencies are considered, a series of limit levels can be calculated for each, which from 500 Hz downwards would all be higher than in the first case. But the criterion must be not to interfere with the audiometric test as a whole; consequently the limiting spectrum is, in effect, set below 500 Hz by the calculations including masking as given above, whereas above 500 Hz masking allowances are no longer relevant, and the limit is set

by the vehicle and headset insulation, together with the absolute threshold level. It takes the form shown in Fig. 4.11.

In practice, almost no limitations on siting the vehicle were encountered. To illustrate the toleration of outside noise levels we show in Fig. 4.11 some examples based on aircraft and motor vehicles. The vehicle noise spectra were derived from measurements relative to work described in reference (9), where a group of observers were required to give judgments of the noise from passing vehicles. The noise spectra of commercial vehicles and of motor-cycles in the judgement classes "noisy" and "excessively noisy" as heard at a distance of 6·5 m were adjusted to a distance of 15 m, which was considered to be more realistic. The resulting spectra are plotted, for the average of each type of vehicle, on Fig. 4.11. It can be seen that the road traffic spectra intrude only at the very low frequencies and



4.11 Toleration of ambient noise levels. The solid line is the permissible octave band spectrum. Symbols: fly-over noise of four-engined jet aircraft, +, curve (a) altitude 80m, landing, curve (b) altitude 600m, steady flight; motor-cycle judged "noisy" to "excessively noisy", distance 15m, ×; commercial road vehicles judged "noisy" to "excessively noisy", distance 15m, O.

errors are therefore only likely for the 500 Hz tests. The aircraft noise, for which severe examples have been illustrated, just approaches the limit in the lower octave bands and again would at most affect very slightly the test at 500 Hz.

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Appendix 5

The mobile acoustical laboratory

by W. C. T. Copeland and E. G. Saunders

The vehicle, shown in Fig. 5.1, is approximately 8·5 m long by 2·5 m wide and 3·5 m high. It is constructed on a Commer forward-drive chassis with the normal wheelbase extended from 4·1 to 4·9 m, and weighs 8·5 tons overall. Fig. 5.2 shows an interior view looking towards the driving compartment.

The permanently mounted apparatus consists of eight channels of amplification, with band pass filters and recording equipment. The input may be either signals from microphones or from tape records, and the display equipment of each channel consists of graphic level recorders and statistical distribution analysers, in addition to conventional visual meter display. Condenser microphones are used with associated cathode followers at the remote end of cables of length 90 m. The microphone cables are carried on motorised drums in compartments on each side of the vehicle below floor level, one being shown with covering flap raised in Fig. 5.1. Central stabilised supplies and calibration signals are provided for each channel. The equipment may be employed in two different modes. In one, up to eight separate channels may be independently used, for example, in determining an overall sound level simultaneously at eight different microphone positions. In the other, one microphone may feed eight channels in parallel, permitting spectrum analysis in eight different frequency bands. A ninth channel is available for the measurement of another parameter such as overall or weighted sound pressure level.

Multi-track tape recorders are carried for central operation, and lightweight precision battery-operated recorders for use when a long connecting cable to the microphone could be a hazard or otherwise inconvenient. For remote recording, communication is provided by VHF radio telephone, or by intercom sets operated over lines in the multicore cables. For general acoustical investigations apparatus is carried for reproducing, by loudspeaker, test signals of various kinds.

The vehicle can be operated from the public mains supply or from its own supply sources, consisting of either petrol generators or

5.1 Mobile acoustic laboratory.

5.2 Mobile acoustic laboratory, interior view looking forward.

batteries connected to dc/ac inverters, with multiway switching to the various loads. The generators are carried in sound proofed compartments, one on either side of the vehicle, as seen in Fig. 5.1, each delivering 1·5 kW. The inverters give a total of 2 kW, one being frequency and voltage stabilised.

Looking in detail at Fig. 5.2, the two racks in the left foreground carry the eight graphic level recorders; beyond them is the power supplies rack. Heavy duty lead-acid cells are carried in compartments below floor level under the hatches seen in the centre foreground. Of the five racks of equipment seen on the right hand side of the figure, that in the foreground is the microphone supplies and control rack. The second and fourth carry the signal amplifiers and filters. The statistical distribution analysers are located on the third rack, whilst the fifth carries the noise producing equipment mentioned earlier.

The vehicle is completed by ventilation, space and water heating facilities, and a console desk for the convenience of the controller.

Appendix 6
Text of handout to factory employees

"Possible effects on hearing in noisy occupations

The Medical Research Council and the National Physical Laboratory are undertaking a joint research programme, at the request of the Government, into the effects of noise on workers in industry. This is needed in order to help the Minister of Pensions and National Insurance in considering whether, and if so, under what circumstances, industrial deafness might attract benefit under the Industrial Injuries Act. It will also help in dealing with the problem of what can be done about preventing or minimising the bad effects of noise.

The Medical Research Council team will visit this factory soon and will first ask a few selected people to help them by answering a simple questionnaire, and submitting to an ear examination. Some will then be asked to have their hearing tested, which is a simple process taking only a few minutes. They will be given an appointment to attend for the test at the start of the working day before beginning their normal noisy work. The management will excuse them from work for this period including any necessary waiting time. Taking part in these tests will not involve any loss of pay.

Later, the National Physical Laboratory team will come to measure the noise in which the selected people work.

The result of your test will be known only to yourself and to the members of the team and will be kept strictly confidential."

Appendix 7

Selection of factories for inclusion in survey

by H. W. Penney

The Ministry of Labour, through the Factory Inspectorate, indicated factories that would be the most likely to present conditions meeting the requirements of the survey, namely reasonable numbers of workers exposed to a noise level of sufficient intensity throughout the working day. The information so provided was examined, and those factories judged to present favourable conditions were invited to co-operate in the survey. An exploratory visit was then made to confirm their suitability and scope before undertaking audiometric examinations of the employees. In the event, the majority of the subjects found in these factories contributed mainly to the retrospective and serial data, because only small numbers of young persons in the prospective category, i.e. with no previous exposure to occupational noise, were located.

Continuous and intensive effort was expended in order to determine probable locations of young people suitable for the prospective part in the investigation. A review was undertaken, based on data obtained from the Ministry of Labour, of some 600,000 boys and girls entering industry from school in the year 1964, and it appeared that only approximately 63,000 were likely to be absorbed into occupations of a type that would yield suitable material for prospective study. Further investigations revealed the wide geographical dispersion of these young subjects and the small numbers of young people entering any one factory, both in terms of actual numbers as well as the numbers entering at a given time. The conclusion was inevitable that the pattern of juvenile employment in general would not permit such investigation on a large scale.

Nevertheless, the Ministry of Labour, in conjunction with the Central Youth Employment Executive, made considerable efforts to find factories where adequate numbers of young people started employment simultaneously, and exploratory visits were made. The results, however, were marginal and only four factories with a suitable intake of young persons were located.

Among the factors limiting the availability of suitable young persons, were

(a) the reluctance of some employers to co-operate in the survey owing to their own difficulties in recruiting sufficient numbers of young people, and the fear that the presence of research workers might create a bad image of conditions in the factory
(b) few young people being placed directly in noisy jobs on first employment
(c) the intermittent nature of most young persons' exposure to noise during their early period of work
(d) the reluctance of boys and girls to enter a noisy industry when there was well paid alternative work available in the area, particularly where new industries are being established
(e) young persons enrolled as apprentices being exposed to different noise levels for varying periods of time in the course of their period of training
(f) the high rate of turnover of young labour which precluded the obtaining of successive audiograms
(g) restriction on the intake of young persons where shift working is in operation or is being introduced.

The number of factories located having reasonable intakes of young people was thus disappointingly small, so that young people in the prospective category are not numerous. This deficiency was somewhat mitigated by the presence in the serial audiometry category of considerable numbers of young persons, who were of age less than 18 years at the time of their initial employment, and whose noise exposure was less than 2 years in duration at the time of the first hearing test.

Finally the stage was reached in 1966 when no more factories could be accommodated within the time-scale of the project. At this point the situation, in terms of numbers of factories, was as follows:

(a) total numbers of factories considered	239	
rejected outright as unsuitable		93
selected for further investigation		146
	239	239

(b) factories selected for further investigations

by preliminary visits	96	134
by exchanged correspondence	38	
factories declining to co-operate		12
		146

(c) summary of results of further investigations

offering favourable conditions for survey	32
marginal interest only	12
considered unsuitable for survey	76
subsequently withdrawing on account of production or reorganisation difficulties	14
	134

Factories participating fully in the survey number 32 and a total of 91 visits were made to conduct hearing tests, as below

1963	6	
1964	22	
1965	25	
1966	26	
1967	12	
Total	91	visits

Conditions suitable to meet the requirements of the investigation were found in the industries and processes summarised below:

Food—sugar refining	packaging of sugar and syrup filling
Iron and steel	dressing and fettling heavy and light castings, grinding, tagging
Boiler making	boiler erection, caulking, chipping, rivetting
Ball and roller bearings	machine operations
Bolts, nuts, screws and rivets	auto heading and screw turning machines and allied processes
Cans and metal boxes	press machines, can lines, body making and wrapping
Sparking plugs	auto machines, tamping and assembly

Bottle fasteners	pressing, assembly of crown cork bottle tops
Motor car manufacturing	foundry work, moulding, core dressing, fettling
Man-made fibres	spinning and drawtwisting
Wool/worsted	spinning and weaving
Thread	spinning, twisting, spooling, hank winding
Silk and rayon	weaving, battery filling
Narrow fabrics	spinning and weaving
Carpet manufacture	weaving, creeling
Stationery and printing	continuous stationery, letterpress and gravure printing

Appendix 8

Otological examination and questionnaires

by Barbara E. Wood

The audiometric field team included an otologist to undertake the examination of personnel who volunteered to participate in the survey, in order to ensure that they were free from existing or previous ear disease, or any other medical condition judged to be incompatible with participation in the tests. This examination was regarded, additionally, as an essential pre-requisite to audiometry in order to maintain a high standard of reliability of the audiometric results. For this purpose certain criteria were used, which are enumerated below.

Staffing

During the period in which the field work was conducted, a number of staff changes were made to accommodate movements of suitably qualified otologists. In consequence the otological work could be regarded as falling into three distinct phases:

Phase 1 July 1962—August 1964
Full-time appointment of an otologist provided from the Ear, Nose and Throat Infirmary, Liverpool.

Phase 2 September 1964—January 1966
Otological services, provided on a sessional basis, mainly from the Royal National Throat, Nose and Ear Hospital, London, W.C.1.

Phase 3 February 1966—September 1967
Full-time appointment of an otologist within the establishment of the research team.

During these phases, the need to maintain as far as possible, the same standards and criteria was particularly emphasised.

Method

The personnel to be examined, after interview by a member of the field team to elicit details of current work and of any previous exposure to noise hazards, were then seen by the otologist. On the occasion of the first and all subsequent tests, the relevant medical history was obtained, and a clinical examination conducted. The procedure of the examination and methods of recording its results, and those of the interview, are set out below. The forms used are reproduced on pages 91 and 92.

In general, the otological examinations were carried out before the audiometric test, although it was occasionally necessary to reverse this procedure to meet the time schedule required at some factories. In all such cases, a brief check was made by the otologist of the subjects' ears before audiometry, to ensure the absence of wax or overt pathology.

The audiograms obtained were reviewed by the otologist and correlated with the clinical findings. Any abnormalities disclosed, including evidence of significant noise-induced hearing deterioration, were explained to the individuals concerned and, subject to their permission, notified to their general practitioner or to the firm's doctor.

The otological examination

The scheme of the otological examination was as follows:

HISTORY

Details obtained of:

(a) earache or discharging ears as child or adult
(b) subject's estimate of own hearing
    (direct questioning where necessary concerning hearing of television, telephone and group conversation)
(c) tinnitus
(d) family deafness
(e) recent cold
(f) severe illness in childhood or later life
(g) head injuries, accidents and operations
(h) treatment with drugs, e.g. antimalarials, streptomycin
(i) any other relevant details

CLINICAL EXAMINATION

(a) *External ears*
Scars; state of meati

(b) *Tympanic membranes*
(i) Appearance classified as follows:
A intact and completely normal, good texture, no retraction, no distortion of cone of light, no fibrosis
B intact but minor changes, loss of lustre, slight fibrosis, slight distortion of cone of light, chalk patches
X intact but gross changes, no cone of light, complete opacity, gross retraction
Y perforation and gross deformity but no active disease
Z perforation and gross deformity plus discharge
(ii) Mobility of drum with Siegles' speculum

(c) *Whisper tests*
carried out where useful and environmental noise allowed

(d) *Fork tests*
equipment:
512 Hz fork, Bárány box
(i) Rinne test
(ii) occlusion test (Bing)
(iii) Weber test
always in two positions, i.e. vertex and frontal regions; results discounted if not in agreement

(e) *Nose and pharynx*

(f) *Pupillary and corneal reflexes*
in cases of sensorineural hearing loss

Criteria for acceptance as "normal" ears

Ears were categorised as "normal" if they complied with the following requirements:
(a) tympanic membranes intact and mobile
(drum classification A and B above)
(b) Rinne test positive

(c) no history of congenital or acquired conditions associated with sensorineural hearing loss, e.g. congenital deafness, meningitis, unconsciousness and/or radiological evidence of fractured skull following head injury, treatment with ototoxic drugs, vertigo, etc.

(d) audiogram compatible with clinical findings

Consideration of subjects with "non-normal" ears

In March 1966 it was decided to reconsider subjects who had hitherto been excluded on grounds of exposure to gunfire, head injury or aural pathology, and fully to assess similar cases presenting in new subjects. It was judged that comparisons between the various groups of non-normal and normal ears might be relevant to the practical assessment of the effects of noise on all exposed persons.

A review of all records of personnel whose audiograms were unacceptable for inclusion in the survey (for reasons other than inability to perform the test or of confused noise exposure) was undertaken, and these subjects designated "pathological" cases. Provided satisfactory noise exposure data were available the majority of these subjects still in original employment were re-examined and re-tested between April 1966 and August 1967, and grouped into the following classification:

P1 Conductive hearing loss.
P2 Vertigo.
P3 Sensorineural hearing loss other than noise-induced.
P4 Exposure to gunfire other than air gun or .22 rifle.
P5 Head injury with definite history of unconsciousness and/or radiological evidence of skull fracture.

A summary of the numbers of persons classified as "pathological", and their distribution in groups, is set out in Appendix 14. These figures cannot, however, in any way be taken as providing information on the proportion of "pathological" subjects to normal subjects in employment at the firms visited during the course of the survey. They are derived purely from the numbers volunteering for the test who were put forward by the firms concerned, in most cases after preselection, and excluded those who in the earlier stages of the survey may have been rejected on the basis of a clinical otological examination as unsuitable for audiometry for the purposes of the survey.

JOINT MRC/NPL WORKING GROUP ON OCCUPATIONAL DEAFNESS

QUESTIONNAIRE

NAME | CHECK NO.________ | SER. NO.________

HEARING TEST APPOINTMENT | Date________ | Time ________

FIRM | CATEGORY

AGE | SEX | DATE OF EXAMINATION

EAR EXAMINATION

R | L

(i) Meatus

(ii) Drum

(iii) Nose

(iv) Throat

(v) History of ear disease

Comments on suitability for audiometry

PRESENT OCCUPATION

(i) What is your job?

(ii) What part of the factory do you work in?

(iii) How long have you been working in the present noise at this firm?

(iv) Have you done any other jobs at this firm?

(v) Are you protecting your ears against noise?

(vi) How do you protect your ears?

NEVER

OCCASIONALLY

DURING PARTICULARLY NOISY PERIODS

MOST OF THE TIME

ALL THE TIME

PREVIOUS OCCUPATIONS

(i) Have you previously worked in a noisy place? (details)

(ii) Have you served in the Armed Forces or the Home Guard? Branch________Dates________

AUDIOLOGICAL HAZARDS

(i) Have you ever fired a gun? (details)

(ii) Have you been knocked out or have you ever received a severe blow to the head?

(iii) Do you know of anything else which may have affected your hearing?

(iv) Is anyone in your family deaf?

CATEGORY (if IV, reason stated)

Joint MRC/NPL Working Group on Industrial Noise and Hearing

RE-TEST QUESTIONNAIRE

Name: Check No.: Serial No.:

Hearing Test Appointment: Date: Time:

FIRM: CATEGORY:

Age: Sex: Date of Examination:

1. Noise Exposure Since Initial Examination

(a) Detail of all jobs, with duration:

(b) If on same job, whether position in shop altered and if so where now located:

(c) Ear protection:

(d) Details of any additional gunfire:

(e) Concussion etc.:

(f) Details of additional history not obtained at first examination:

2. Clinical Examination

(a) History

(b) Meatus

(c) Drum

(d) Nose

(e) Throat

(f) Additional history of ear disease

	Right Ear	Left Ear
(g) Rinne test (500 Hz)		
(h) Weber test (500 Hz)		
(i) Fit for Audiometry		

3. Remarks

Appendix 9
Measurement of noise exposure

by W. C. T. Copeland and D. W. Robinson

Outline of procedure

To eliminate unnecessary audiometry and waste of factory working time, a preliminary inspection was made of the noise environment in each of the preselected factories. An inspection of the machinery, the processes and the modes of working, conducted in consulation with supervisory staff, helped to establish the broad pattern of noise exposure of the personnel. Exploratory noise measurements with a portable sound level meter and octave band analyser showed whether it was likely to be profitable for the audiometric team to seek subjects from the whole, or selected parts, of the factory, or whether not to proceed at all. In the former case further action was deferred until other factors had been weighed up, notably the numbers of potentially suitable subjects from the audiometric standpoint, or the rate of turnover of personnel which might effect the usefulness of the site for serial audiometry.

The preliminary measurements indicated whether the noise, or noises, in a certain area met the requirements of being reasonably steady and continuous, not markedly impulsive in character, and high enough in level, namely 80 dB(A) or above. Subsequently, when the list of suitable subjects had been settled, a more elaborate noise measurement procedure described below was carried out. This visit usually took place after the first audiometric tests, the noise measurement team following their own economical itinerary independently of the audiometric field team. On the second visit, the pattern of movements of workers and of the various process operations was examined in greater detail, in order to decide microphone positions. The object was to obtain noise exposure values representative of the average day by day environment to which each subject was exposed. Practical points had also to be taken into account, such as the risk of trailing cables being cut or themselves becoming a safety hazard.

In general the shadowing technique, that is to say following the subject around with a microphone close to his ear, was adopted in those cases where the dominant noise source was one so close to the

worker that the distance from the ear was a material factor, or where the worker tended to change position from time to time using noisy hand-held tools, as in fettling, chipping, burnishing or welding. At the other extreme there were some situations in which the noise was both steady and uniform over a substantial area, permitting a straightforward measurement. The majority of cases were intermediate in character, necessitating sampling on a space and time basis, and yielding an assessment of noise exposure which covered the activities of several workers by aggregating the results of measurements at a number of carefully selected fixed stations. This technique was more economical of measurement and data reduction time than the shadowing method, and could be used to cover many different situations; for example cases where it could be ascertained that operatives changed from one machine to another or the type of work they were doing on one machine, but at intervals too long for the shadowing method to be applied. It was also appropriate in cases where workers' jobs took them to different parts of the factory floor, or into areas with different noise levels, more or less randomly. If, in the course of such excursions, the worker in question was known to reside for appreciable periods in the close proximity of loud noise sources this was taken into account. For the noise sampling method, as many examples as possible of each different noisy process were selected and the microphone set up in the position typical of the operative even though the machine was not at the time of the noise survey being manned by personnel selected for audiometry. The ensemble of measurements assigned to an individual generally lay within a compass of 5 dB(A), due in many cases to the fact that variations which would otherwise have occurred from point to point were smeared by general reverberation. Sometimes larger deviations were found, for example when the set of measurements included one or more predominant sources measured at a short distance. These cases were accepted cautiously, the criterion being that the pattern of noise exposure, whilst variable in space and perhaps also on the short time scale, remained broadly speaking the same from day to day and adequately typified the variations encountered by the workers within that area. Cases were excluded where the overall noise climate was liable to change radically in periods of weeks or months, and individuals were excluded on the corresponding basis, that is where it was forecast, or had been recorded, that they spent periods of this order in widely different noise levels. A number of such exclusions

occurred on later review, usually as a result of the second or subsequent visits of the audiometric field team, and was an appreciable factor in the attrition of numbers from various causes that resulted from the rigorous requirements of the investigation.

Method of measurement

The noise measurements, except at the preliminary stage, were obtained by means of the comprehensively equipped mobile laboratory described in Appendix 5. To maintain flexibility in the subsequent correlation of noise exposure with hearing levels, noise measurements of various kinds were made; but practical considerations and the essential requirement of using compatible means of expression in widely differing situations led to an early decision to limit the possibilities. As an example of a measure which might be of significance in particular cases but which could not be entertained for dealing with several hundred different situations on a uniform basis, we should mention narrow band spectrum analysis. Oscillographic recording of sound waveforms was likewise judged to be of too detailed a character to be either practical or useful in the present state of knowledge concerning noise-induced hearing impairment. On the other hand it seemed to us to be unnecessarily cramping to rely on a single noise parameter, which would have had to be selected quite arbitrarily. On the basis of accumulated experience from other research work and a preference for the use of established principles sanctioned by international standardisation for general acoustical purposes, we accordingly elected to characterise each noise by 12 parameters as defined below. This, naturally, was an equally arbitrary decision but it opened up the possibilities of a great number of correlations with derived quantities, such as sound levels with different frequency weightings. Later experience vindicated this decision which, once made, had to be adhered to without alteration: the correlation between hearing loss and noise exposure turns out not to be very sensitive to the choice of the noise parameter within certain limits. To be more accurate, the influence of other sources of variance, notably individual susceptibility, is such that tests of the relative significance of different noise parameters are unavoidably insensitive. Our choice of 12 parameters was guided by the principle that spectral distribution and temporal variations were likely to be the main factors, next in importance to the absolute sound intensity, and of these the first was

the more significant. To characterise temporal variations we adopted the method of analysing the statistical distribution of the instantaneous value of the A-weighted sound level, the output data being in the form of sets of four numbers designated L_{A50}, L_{A20}, L_{A10}, and L_{A2} (see glossary in Appendix 1). The spectral distribution was given by octave band analysis in the form of eight numbers, namely the sound pressure levels in the octave bands with respective centre frequencies 63, 125, 250, 500, 1000, 2000, 4000 and 8000 Hz, designated by L with the appropriate suffix, e.g. L_{63}. The octave band sound pressure levels were not amplitude-analysed, and correspond to 50% on-time level, analogous to L_{A50}. The instrumentation for these measurements is referred to in Appendix 5; one ½-inch condenser microphone (Brüel and Kjaer type 4133 or 4134 according to circumstances) was connected to nine parallel channels of which one led by way of an A-weighting network to the statistical distribution analyser (Brüel and Kjaer type 4220) and the other eight to a bank of parallel octave filters and level recorders. As described in Appendix 10, the measure L_{A2} turned out to be of importance; the octave band data were used to compare the merits of different rating procedures that have been proposed elsewhere, and finally to determine in broad terms the relation between the spectral distribution of noise and the characteristics of the typical noise-induced audiogram.

For a steady noise, the values L_{A50}, L_{A2} etc. converge to a single value, namely the A-weighted sound level as ordinarily defined which would be read directly from the level recorder. Intermittencies or fluctuations in the noise cause them to differ, the higher the excursions of the instantaneous value the less the time for which they persist. From the way these quantities are defined, i.e. the level exceeded for the percentage of time indicated by the suffix, it follows that distinctions are not made between fluctuations that are rapid and those that are slow except insofar as the time constants of the instrumentation set a limit to the resolution of very rapid changes. A further arbitrary decision had therefore to be made concerning the response time of the measuring chain. For this we employed Brüel and Kjaer type 2305 level recorders with the controls set to the equivalent of the "fast" response of standard sound level meters as specified by the International Electrotechnical Commission (1). The response time is of the order 90 ms and though probably not ideal for the purpose it is as near as one can attain in standardised instrumentation to the time constants concerned in the human auditory system.

The magnitude of the difference ($L_{A2} - L_{A50}$) ranged generally from 0 to 10 dB but was as much as 15 in exceptional cases. The corresponding differences between the intermediate amplitude-analysed sound levels L_{A20} and L_{A10} and between these and the 2nd and 50th centile values were found, in the majority of noise environments, to be related through constant factors, so that the intermediate centiles contributed little additional information. Moreover, the various intercentile differences indicated that the distributions of sound level with time were for all practical purposes Gaussian. Under these circumstances, L_{A50} is equal to the mean level and the noise climate can be succintly expressed in terms of the equivalent continuous noise level L_{Aeq} given by the equation

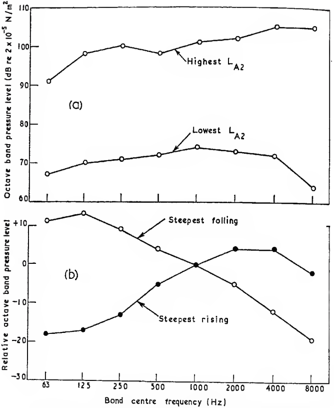
$$L_{Aeq} = L_{A50} + \sigma_L^2/8{\cdot}68$$

where σ_L is the standard deviation of the fluctuations of L_A about its mean. From the properties of the Gaussian distribution the standard deviation is given approximately by $\sigma_L = \frac{1}{2}(L_{A2} - L_{A50})$. In future studies we should aim to measure this quantity directly, but its applicability did not become apparent until a late stage in the present work.

It is important to note that excursions of sound pressure are handled by our instrumentation on the RMS basis smoothed to an extent determined by the time constant of 90 ms used. Impulses which are substantially shorter than this, therefore, do not appear at the output of the level recorder as identifiable spikes, nor show up as differential readings on the 2% and 50% statistical registers. The existence of specialised relations between hearing loss and parameters of impulse sounds other than those derived from the RMS sound pressure have been suggested in the literature (2). For the purposes of the present investigation noises consisting predominantly of impulses were deliberately excluded, for example those from drop forges. Some of the noise environments nevertheless contained impulsive components, for the reason that only by retaining them could we extend the upper end of the noise level range. Situations do not seem to occur very widely in which very high levels are accompanied by a steady, continuous and non-impulsive character of the noise. As mentioned above, the presence of reverberation tended in these cases to diminish the relative importance of the impulsive components.

In planning the investigation, we were aware that fluctuations of noise level would occur on different scales of time and that our instrumentation could not of itself discriminate in this regard. In the presence of noise resulting from metal striking metal, such fluctua-

tions might be resolved by time analysis of the order milliseconds up to a second; changing loads on a machine might entail variations of the order seconds to a minute; semi-continuous processes might produce steady noise for minutes or hours followed by quiet or a different noise; workers might move around the workshop or do



9.1 (a) Octave band spectra of the noise with highest and lowest occurring values of L_{A2} to illustrate the range.
(b) Limiting shapes of the octave band spectra encountered.

different jobs on the same machine. We judged though without any strong foundation for so doing, that short-term and long-term fluctuations ought to be regarded as distinct in relation to their possible influence on hearing until and unless shown otherwise. There is no dividing line except an arbitrary one, but we adopted the rule that if a noise remained the same for ten minutes or more and then clearly changed in level or character we would deem it to be constant on the short term. This enabled us to give a definite meaning to the output of the statistical distribution analyser by adopting a period of some ten minutes as the sampling period. If a long-term change occurred, using this definition, it implied a different noise which was to be sampled separately. The distinctions that we make between the "quasi-peak" sound level L_{A2} and the mean prevailing level L_{A50}, therefore, refer to fluctuations on the short time scale, typically seconds or tens of seconds. Sampling periods were selected, after a day or two's familiarisation with a factory, to be representative of a day's working.

In all, 280 sets of personal noise parameters were assigned, based on a much larger amount of raw data. We show in Fig. 9.1 the upper and lower bounds of the octave band spectra encountered. To obtain part (a) of the diagram, the noises were ranked in order of ascending value of L_{A2} and the octave band spectra for the highest and lowest are shown. In part (b) the octave band spectra of all the noises were ranked from high to low in terms of the spectrum slope parameter S_1 (see Appendix 10, section 4) and the illustration shows the examples with the strongest rising and falling tendency, arbitrarily pegged to a common value of 0 dB in the 1000 Hz band. Referring to Fig. 9.1 (a), the highest individual values of octave band pressure level coincide with the plotted points in the bands 125, 250, 1000, 4000 and 8000 Hz, but occur as isolated maxima in certain other spectra as follows:

63 Hz,	maximum value	97 dB
500 Hz,	,, ,,	103
2000 Hz,	,, ,,	104

References

1 International Electrotechnical Commission, Geneva 1965. *IEC Publication 179*.

2 Coles, R. R. A., Garinther, G. R., Hodge, D. C. and Rice, C. G. *J. acoust. Soc. Amer.* 1968, **43**, 336.

Appendix 10

Relations between hearing loss and noise exposure

Analysis of results of retrospective study

by D. W. Robinson

Scope

Section 1 of this Appendix contains an outline of the process of data analysis from the retrospective study, concluding with a mathematical formula which summarises the principal results. Full details of the derivation of this formula, together with statistical information, are contained in Section 2. A practical procedure for estimating the risk of noise-induced hearing loss is given in Section 3. The remaining Sections deal with the effects of different spectral distributions of the noise, with differences in the results classified by sex, and with refinements of mathematical representation.

Attention is drawn to the main results, which are presented in Section 1.3, Tables 10.1, 10.2 and 10.3, and on Fig. 10.17.

1. Outline

1.1 INTRODUCTION

The results of the retrospective audiometric survey of 759 noise-exposed subjects, supported by 97 non-exposed controls tested under identical conditions, together with noise measurements and exposure histories for the exposed group, comprise the experimental data which are studied in this Appendix.

The criteria for selecting the subjects, the details of otological examination and of the associated personal questionnaire, as well as the procedure adopted to assign noise exposure values to each individual are described elsewhere in this Report and it suffices here to state that any hearing impairment observed could be attributed with reasonable assurance to the noise, to presbycusis (in the case of older subjects), or to both; and that the impairment could be associated with a well-defined and constant history of daily exposure to known noise levels.

Thus the raw material was in the form of subject data (serial

number, age, sex, months of continuous daily exposure), hearing levels at six frequencies for both ears, and noise data (octave band sound pressure levels and statistical distributions of A-weighted sound level). Preliminary manual analysis began in 1965 when the results of 418 noise-exposed cases were to hand. Master data tapes for KDF9 computer analysis were prepared in 1966 at the stage of 581 cases, and these were updated in 1967 to include the remaining 178 for the final analysis leading to the mathematical representation of the results. The exposure durations of the subjects, apart from controls, ranged from 1 to 600 months; the noise levels from about 75 to 120 dB(A).

1.2 ANALYTICAL PROCEDURE

The various stages of data reduction which we followed and which led finally to a mathematical model of unexpected economy of expression, were based on the following considerations.

(a) The observed hearing level H_O',* subject to the errors inherent in audiometry, can be regarded as a function of the three independent variables noise level L, exposure duration T and subject's age N. Of these, L and T were subject to some uncertainties but these had been kept within acceptable bounds by the rigorous field-work procedures. The variable T is by its nature unidimensional, but this is obviously not true of L so that this general symbol here represents any of the possible permutations derived from the various noise measurements, as described in Appendix 9. N alone was known with practical certainty.

(b) The relationship between H_O', L, T and N would differ from subject to subject but might exhibit some consistent trends, such that the functional relationship could be stated in statistical terms.

(c) The components of hearing loss, expressed in decibels, due to noise exposure and age (presbycusis) were assumed to be additive. Thus by subtracting out the presbycutic hearing loss, the data would be reduced to a relation between three variables, H, L and T. Since it is impossible to resolve the components of loss experimentally in a study in which both age and noise exposure are advancing together, it is necessary to resort to other sources of information on presbycusis and to apply a uniform correction to all measured hearing levels. Published experimental data on presbycusis indicate large individual variations and even the mean

* The symbolism employed here is explained in Appendix 2

results for rather large groups of subjects are discordant. However there is broad agreement that the effect begins to be noticeable around 25 years of age, increases at an accelerating rate, and is progressively greater with audiometric frequency beginning with about 500 Hz.

(d) The relation between the effect H on the one hand, and the causes L and T on the other might be reducible to a relationship between H and a composite function of L and T representing total noise exposure. This question is discussed in Appendix 11 in which the postulate is shown to be valid.

(e) Given a first-order approximation to a functional relationship between H and L, T and N, the deviation between observed and calculated H would be composed of variance due to (i) measurement uncertainties of the variables (ii) deviations of the function from reality in respect of the "average" subject, and (iii) personal variations of susceptibility to noise-induced hearing loss. Components (i) and (iii) reside in the data, and in the nature of things cannot be eliminated. Component (ii) can be varied by altering the function, e.g. by selecting different measures of L, or different presbycusis corrections. The search for minimum total variance is thus equivalent to the search for the correct functional relationship.

Brief acquaintance with the data at an interim stage indicated that item (iii) was predominant. Under these circumstances the sensitivity of the total variance to changes in the formulation of the functional relationship between the variables, or in the choice of the measure L, could not be very great. By the same token, when such changes affected the variance in a systematic way it could be assumed that they were correspondingly significant, and a second approximation to the functional relationship might be deduced or suggested.

The schedule of analysis that was actually followed was conditioned party by the timetable for interim reports, partly on the plan outlined above, and finally on an inductive leap that could not be foreseen or preprogrammed, to a concise mathematical and nomographic summary of the entire data. An outline of the steps follows below; fuller details will be found in Section 2.

(i) *Stage of 418 results*

Manual analysis suggested that the noise measure L_{A2} was more relevant than the following alternatives: L_{A50}, L_{2000},

NR*; also that the subtraction of a standard presbycusis correction was beneficial to the data reduction.

(ii) *Stage of 581 results*
A variety of correlation and regression analyses using KDF9 computer confirmed the significance of the measure L_{A2}, and gave quantitative indications with regard to presbycusis correction. Attention was mainly centred on the audiometric data for 4 kHz. Similarities of mean H values between cells having certain combinations of L_{A2} and T were noticed and by combining such cells into 7 super-groups it was shown by manual analysis that a composite exposure measure of the form $L_{A2} + k \log (T/T_O)$** with k in the neighbourhood of 10 tended to summarise the data with reduced variance. Further, the mean audiograms for the super-groups formed a series of curves which could be closely represented by a universal curve together with a multiplying factor related to the exposure measure. Later analysis (see iii below) caused us to modify this representation in favour of another, which is founded on a fundamentally simpler conception.

(iii) *Stage of 759 results*
The indications from (ii), with regard to the most relevant noise measure L_{A2} and to the presbycusis correction, were accepted as decisive and the analysis was extended to all audiometric frequencies.

The work described in Appendix 11 was next carried out, and it confirmed that the total noise exposure could be expressed in the form $E_{A2} = L_{A2} + 10 \log (T/T_O)$, a quantity to which we have given the name noise immission level.

Second-order curve fitting in the manner described in Appendix 11 now showed that the variation of H with E_{A2} was similar at each audiometric frequency except for a constant shift along the E_{A2} scale, and that the cell mean hearing levels for all frequencies could in this way be normalised on a single curve without exceeding the variance of the data points at any one frequency. This result appeared to us to be of

* Noise Rating number, determined from the octave band spectrum in accordance with the procedure described by Kosten and van Os (1).

** T_O is an arbitrary reference duration.

cardinal importance, and to transcend the provisional model (see ii above) concerning the form of the mean noise-induced audiograms. The later result admits of the straightforward interpretation that the mechanism of damage to hearing is essentially the same over the length of the cochlea, the variation with frequency resulting simply from the fact that the response to cochlear excitation by broad band noise varies in magnitude with position along the cochlea. The hearing loss data, thus normalised in terms of a composite parameter $E' = L_{A2} + 10 \log (T/T_O) + \Delta E_A$ (ΔE_A being a constant depending on the frequency only), were at this stage still in the form of cell means, 20 per frequency. The collapse of all frequencies on to one diagram, however, increased the number of points defining the curve to 120 and it was now feasible to look for a more refined functional relationship $H = f(E')$, freed from the objections to the first and second degree curves so far used, namely that their terminal behaviour outside the range of interpolation was unrealistic. The form

$H = a \left\{ 1 + \tanh \frac{E' - E_O}{\mu} \right\}$ meets the logical requirements,

and provisional values of a, E_O and μ were obtained by a method of successive approximation. With slightly different values of the parameters a, E_O and μ the same function was found to fit equally well to the cell medians, and in the sequel this acquired greater importance.

As already noted, the major component of variance is that between subjects and it was clear at an early stage that in stating the results it would be as important to represent the dispersion as the central tendency. A systematic trend regarding the dispersion had been observed at Stage (i), and again at Stage (ii): starting from the control (non-exposed) group with a nearly Gaussian distribution of hearing levels, and considering exposed groups for progressively higher noise level or duration, the distributions changed progressively to a skewed platykurtic form. At stages (ii) and (iii) it was found that any particular distortion of the Gaussian distribution could be associated with a particular noise immission level, that is to say the higher moments of the distribution, like the mean value (first moment) as already described, appeared to be

uniquely related to noise immission level irrespective of whether this resulted from short exposure to loud noise or prolonged exposure to a lower level. Furthermore, by examining the cumulative distributions for each of the supergroups at each of the 6 audiometric frequencies it was evident that the progression of the distortion was a universal trend, the only difference being that the distribution for a low frequency (e.g. 1 or 2 kHz) and a given immission level coincided in form with that for a higher frequency (e.g. 4 kHz) at a lower immission level. To quantify the underlying significance of this observation, we treated the centiles (2, 5, 10, 25, 75, 90, 95 and 98) of the supergroup distributions exactly as had previously been done with the mean and median (50th centile) and it was found that to collapse the results for all frequencies to identical parallel curves it was only necessary to apply the same shift constant ΔE_A as found for the medians. The final comparison between the experimental results and the generalised mathematical model showed that the entire results could be summarised by a single expression.

1.3 SUMMARY OF PRINCIPAL RESULTS

The noise-induced component of hearing loss to be expected in a given percentage p of a normal population subjected to habitual daily exposure to a noise level L_{A2} over a period of time T can be written

$$H = 27{\cdot}5 \left[1 + \tanh \left\{L_{A2} + 10 \log (T/T_O) + u_p - \lambda_i\right\}/15\right] + u_p$$

where λ_i is a constant depending on audiometric frequency, as given in Table 10.1, T_O is a reference duration and u_p is a constant depending on the selected percentage p as given in Table 10.2.

The tabulated values of λ refer to the mixed population of males and females on which the analysis is founded. We refer in Section 5 below to a sex-linked difference in the magnitude of presumed noise-induced hearing loss. If it is desired by the user of our formula to make a distinction between the expected hearing losses for men and women, he should add $-1{\cdot}5$ and $+1{\cdot}5$ dB respectively to the values of λ given in Table 10.1.

It is often more convenient in practice to express the noise level in terms of L_A in dB(A) as read on a sound level meter, rather than in the form L_{A2} which requires additional instrumentation; the average relation between the two (based on the 280 different noises in our survey) may be taken as $L_{A2} - L_A = 3{\cdot}7$. For use of the formula with

TABLE 10.1
Frequency parameter λ in H-function

Audiometric frequency (kHz)	λ (dB)			
	Noise level given in form L_{A2}		Noise level given in form L_A	
	T_O = 1 year	T_O = 1 month	T_O = 1 year	T_O = 1 month
0·5	133·7	144·5	130·0	140·8
1	130·2	141	126·5	137·3
2	123·7	134·5	120·0	130·8
3	118·2	129	114·5	125·3
4	116·2	127	112·5	123·3
6	119·2	130	115·5	126·3

TABLE 10.2
Centile parameter u in H-function

Centile p		u (dB)
Susceptible ears		
	1*	13·8
	2	12·1
	3	11·1
	5	9·8
	7	8·7
Decile	10	7·6
	15	6·0
	20	5·0
Quartile	25	4·0
	30	3·1
	40	1·5
Median	50	0
	60	− 1·5
	70	− 3·1
Quartile	75	− 4·0
	80	− 5·0
	85	− 6·0
Decile	90	− 7·6
	93	− 8·7
	95	− 9·8
	97	− 11·1
	98	− 12·1
	99*	− 13·8
Resistant ears		

*Extrapolated.

L_A in place of L_{A2}, we have given the appropriately modified values λ_i in Table 10.1 but, to the extent that we have found L_{A2} to correlate better with hearing loss than L_A, the simplified procedure will be less exact for strongly fluctuating noise environments.

H may be regarded as an age-corrected hearing level relative to controls, or as the presumed noise-induced hearing loss, these two concepts being equivalent in the case of persons suffering no other impairments. For ordinary practical purposes, the actual hearing level H′ as determined by an audiometer is a more convenient quantity than H. The value of the expected hearing level relative to controls H′ may be obtained from the relation:

$$H' = H + C_i\,(N-20)^2 \quad (N > 20)$$
$$H' = H \quad (N \leqslant 20)$$

where C_i is a coefficient depending on frequency, as given in Table 10.3, and N is the age in years. The right-hand term restores the presbycusis correction which was subtracted throughout the analysis.

The result can be written most economically in the form above, but this is readily converted into nomographic form for ease of application. The chart and the manner of using it are described in Section 3.

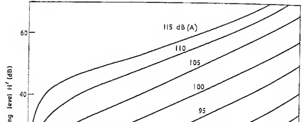
TABLE 10.3
Age-correction coefficients

Audiometric frequency (kHz)	C
0·5	0·0040
1	0·0043
2	0·0060
3	0·0080
4	0·0120
6	0·0140

It will be noticed that the argument of the hyperbolic function is a quantity having the nature of a decibel level and that duration enters through its logarithm. The characteristic shape of the H-function in terms of the argument of the hyperbolic tangent is seen in the lower part of the nomogram (Fig. 10.17); it grows at a rate which accelerates at first and finally retards towards an asymptote. This form is convenient for use, but it obscures the nature of the intrinsic relationship between H and T. Fig. 10.1 shows the shape of the function H in linear measure for a few typical cases, and in this form it is striking

how rapid is the initial onset of noise-induced hearing loss in relation to the later deterioration rate.

In Fig. 10.1, the ordinate is H′, the presbycusis correction having heen restored in such a way that the abscissa may be read as suhjects' age on the assumption that they entered noisy employment at age 20. Other examples can easily be constructed, for medians or centiles and for various noise levels and durations, from the equations or the nomogram. It is implicit in our results that the physical quantity controlling noise-induced hearing loss is the noise immission level, not the noise level or the duration *per se*. Accordingly the charts appear to he appropriate for assessing the expected loss due to a succession of different exposures. For example, one year in a level of 95 dB(A) followed hy 4 years in 89 dB(A) should be equivalent to 2 years at the higher level, since the total immissions are equivalent. Exposures are thus cumulative and it should make no difference (except in respect of age) if, in the above example, the noise doses were separated hy a period in quiet employment.



10.1 Comparison of the rapid onset of noise-induced hearing loss with the effect of ageing which is slow at first. Frequency 4 kHz.

2. Details of analysis

This chapter, which is intended for detailed reading only, is an amplification of (i) (ii) and (iii) of Section 1.2.

2.1: STAGE (i) — 418 SUBJECTS

Method:
Manual sorting into 20 cells, (4L × 5T)

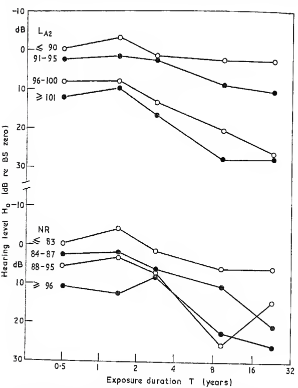
Frequency considered:
4 kHz.

Object:
(a) to obtain a first approximation to the variation of H′ with T for constant L.
(b) to obtain preliminary indications on the influence of various L measures.
(c) to determine whether the extraction of a standard presbycusis correction would reduce the scatter of H, compared with H′.

Procedure:
Sorting by T produced approximately equal numbers when the boundaries were chosen as follows: 1–12, 13–24, 25–48, 49–168, 169–600 months. As it happens the geometric means of these intervals are spaced roughly equally in terms of log T which was unplanned but convenient. The subjects falling within each exposure band were next sorted into 4 noise classes, the boundaries of which were chosen to be the same for each exposure class. The four L-measures selected were L_{A2}, L_{A50}, L_{2000} and NR. The boundaries were chosen differently for each L-measure, so that the numbers of subjects within each cell were equalised so far as possible. The smallest cell contained only 9, the largest over 30. The noise level boundaries resulting from this sorting were as follows:

L_{A2}	⩽90,	91–95,	96–100,	⩾101 dB(A)
L_{A50}	⩽86,	87–90,	91–97,	⩾ 98 dB(A)
L_{2000}	⩽79,	80–84	85–90, ,	⩾ 91 dB
NR	⩽83,	84–87,	88–95,	⩾ 96

In the nature of this procedure, corresponding cells for different L-measures comprised some individual subjects who were the same and some who were different, the interchanges reflecting the partial independence of the measures selected. Cell means and standard deviations were calculated for H_4 (mean of left and right ear) and plotted against log T with L as parameter. Qualitatively, the "best" (i.e. most plausible) trend was exhibited by the L_{A2} data, the



10.2 Illustrating how hearing loss is correlated more closely with one measure of noise (dB(A)) than another (NR). Frequency 4 kHz, 418 subjects.

"worst" by NR. These two results are illustrated in Fig. 10.2. To express the relative merits of the L-measures quantitatively, at least in an approximate way, straight lines were fitted to the data and the mean square deviations of the cell means about these lines calculated. The result is shown in Table 10.4.

TABLE 10.4
Comparison of regression variance of cell means for various noise measures

Noise band	Noise measure	Mean square deviation (dB^2)
1 (Low)	L_{A2}	1·7
2		3·7
3		4·2
4 (High)		10·5
1 (Low)	L_{A50}	2·2
2		11·4
3		18·5
4 (High)		2·8
1 (Low)	L_{2000}	2·5
2		10·7
3		34·5
4 (High)		2·2
1 (Low)	NR	3·8
2		7·7
3		31·4
4 (High)		17·4
All (1—4)	L_{A2}	5·0
,,	L_{A50}	8·4
,,	L_{2000}	12·5
,,	NR	15·1

The average variance (fifth block of the Table) suggests a rather marked advantage of L_{A2} over each of the other measures, and in the interests of economy NR was eliminated from further analysis. The H_O data in Fig. 10.2 and Table 10.4 were corrected for presbycusis by the amount shown in Table 10.3. Similar results were obtained with the uncorrected data H_O', i.e. the order of preference of the noise measures L_{A2}, L_{A50}, L_{2000} and NR was unchanged.

To compare the effects of correcting or not correcting for presbycusis, the variances within corresponding cells were examined (in this case the intersubject variance, not the variance of cell means). To facilitate the comparison of the 20 pairs of values they have here been averaged over noise bands and over exposure bands respectively in Table 10.5. The L_{A2} analysis was used.

TABLE 10.5
Comparison of variance before and after age-correction

Group	Variance (dB^2)	
	Age-corrected	Uncorrected
All exposure durations, low noise	108	98
,, ,, ,, 2nd noise group	185	219
,, ,, ,, 3rd noise group	201	207
,, ,, ,, high noise	202	213
All noise levels, exposure 1–12 months	139	123
,, ,, ,, ,, 13–24 ,,	119	128
,, ,, ,, ,, 25–48 ,,	156	169
,, ,, ,, ,, 49–168 ,,	216	217
,, ,, ,, ,, 169–600 ,,	240	286
Grand average	174	184

The conclusions from this analysis were regarded as tentative but could be summarised as follows:

(a) correlation of hearing level with noise was highest when the latter was expressed as L_{A2}.
(b) variance within the hearing levels was marginally reduced when an allowance for presbycusis was included.
(c) to a first approximation, hearing level increased uniformly with the logarithm of the exposure duration, the rate increasing progressively with the noise level L_{A2}.

2.2 STAGE (ii) — 581 SUBJECTS

2.2.1 *Linear regression analysis*

Starting point:
The results from Section 2.1 suggested a more systematic para-

metric analysis based on the first-order model i.e. the approximate assumption that H_O varies linearly with log T.

Method:

Computer sorting into noise bands, and linear curve fitting between H_O and log T within each band.

Objects:

(a) to obtain further indications as to optimum noise measure.

(b) the same, with respect to presbycusis.

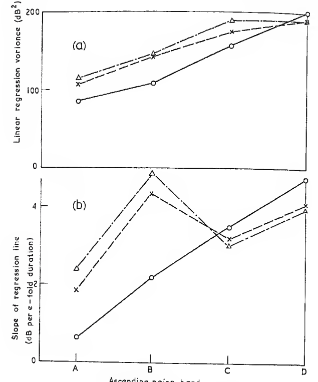
(c) in the light of (a) and (b) to finalise a first-order model, for the results at 4 kHz, regarding the relation between average presumed noise-induced hearing loss, noise level and duration of exposure.

Procedure:

KDF9 was programmed to sort the 581 subjects into noise bands (usually 4 or 6) with preselected boundaries, either in terms of L_{A2}, L_{A50} or L_{2000}; the individual hearing levels for each frequency were programmed for presbycusis correction in a factored manner, i.e. the corrections according to Table 10.3 could be multiplied by an arbitrary factor m (0, 0·5, 1 and 2 were used); the corrected hearing levels H_O were then fitted, for each noise class, by the least-squares method to a straight line in the form $H_O = a + b \ln (T/T_O)$; the coefficients a and b and the residual variance about the straight lines were printed out.

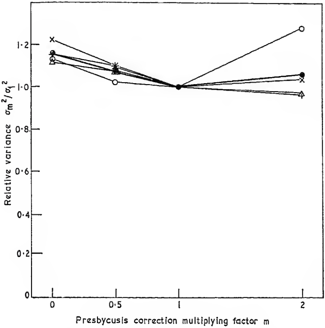
The conclusion with regard to noise measure selection was based on two indications illustrated in Fig. 10.3(a) and (b). In (a) is shown the regression variance (for m = 1; 4 kHz) in a 4-noise-band analysis. Except marginally in the case of the high-noise band, the indication favours L_{A2}. Fig. 10.3(b) shows the corresponding regression coefficients b. These slopes would be expected to increase progressively with the noise level, and this is the case with L_{A2}. Using the other noise measures the slopes were irregular and the corresponding regression lines intersected in an implausible manner. This additional qualitative support for the selection of L_{A2} was taken, from this point on, to be sufficiently decisive. Fig. 10.4 illustrates the change of regression variance, according to the coefficient m, in the factored presbycusis correction. Averaged over the 4 noise bands (L_{A2}) the variance is least somewhere between $m = \frac{1}{2}$ and m = 2, although the absolute variation is too small to

permit of a more precise conclusion. It should be noted, however, that m is an artifact and that $m = 1$ corresponds to a smoothed version of the experimental data on presbycusis due to Hinchcliffe (2). It is therefore quite encouraging to find that a value in the



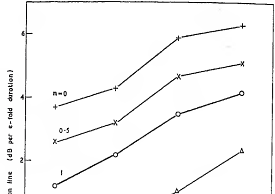
10.3 Aspects of linear regression of age-corrected hearing levels (factor $m = 1$) against log duration of exposure for 4 noise bands and 3 noise measures. The superiority of the measure L_{A2} is clear. Frequency 4 kHz; 581 subjects. Symbols: L_{A2}, ○; L_{A50}, ×; L_{2000}, Δ.

neighbourhood of m = 1 is thrown up by this highly indirect procedure. Fig. 10.5 gives qualitative support to Fig. 10.4. It shows the regression coefficient b for each noise band with m taken equal to 0, 0·5, 1 and 2 respectively. The effect of correcting H_0' for presbycusis is broadly to reduce the slope b of the regression lines, because the older subjects for whom the correction is greatest automatically tend to be those with the greatest exposure durations T. An unrealistically large factor m, however, artificially over-corrects the older subjects' hearing loss with the result that the

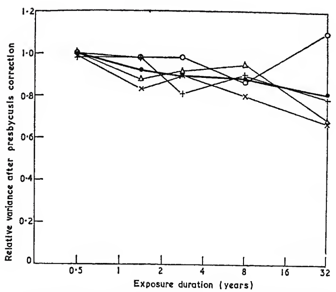


10.4 Residual variances for the regression of age-corrected hearing level, with various age correction factors m, on log duration of exposure. Parameter, noise level. The variance is reduced by subtracting out an age correction, Frequency 4 kHz, 581 subjects. Symbols: L_{A2} ⩽89, o; 90–94, ×; 95–99, +; ⩾100, Δ. Mean of all bands, •.

slope eventually becomes negative. This would imply that hearing improved with noise exposure and is contrary to commonsense. On these grounds the factor m = 2 appears to be too great, as Fig. 10.5 illustrates. A supplementary analysis in the manner of Section 2.1 was also run through the computer, with the 581 data divided into 20 cells, $4L_{A2} \times 5T$. The variances within cells were computed with and without standard presbycusis correction (i.e. m = 0 and m = 1) and the ratios plotted in Fig. 10.6. With one exception, the 20 cell variances were reduced when the correction was applied, and as might be expected the average effect was



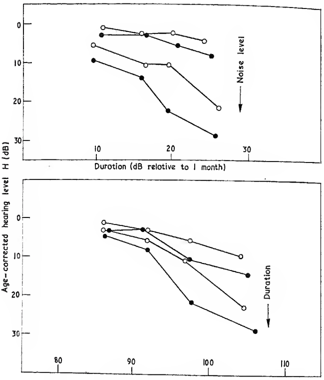
10.5 Regression coefficients for the regression of age-corrected hearing level on log duration of exposure for different noise bands. Parameter, correction factor m. These data corroborate Fig. 10.4. Frequency 4 kHz, 581 subjects. Symbols: m = 0, +; m = 0·5, ×; m = 1, ○; m = 2, △.



10.6 Reduction of variance of age-corrected hearing levels by use of correction factor m = 1. Parameter, sound level L_{A2}. Frequency 4 kHz, 581 subjects. Symbols: L_{A2} $\leqslant$90, o; 91–95, ×; 96–100, +; $\geqslant$101, Δ; mean of all bands, •.

greatest in the long-duration cells where the older subjects tended to congregate. The reduction of variance here amounts to 20% and considering the large intersubject variances (see for example Table 10.5) seems to be highly significant evidence for the hypothesis that presbycusis and noise-induced loss can be considered to be independent and additive. Our conclusion was that Hinchcliffe's smoothed results, represented by our Table 10.3, are appropriate for correcting out presbycusis. In the sequel this was done routinely. The mean results at this stage are summarised in Fig. 10.7 which shows the presbycutically corrected hearing levels (relative to controls) in 4L × 4T cells plotted against log T with L_{A2} as parameter and against L_{A2} with T as parameter respectively. The similarity of these diagrams led to the exploration of a composite

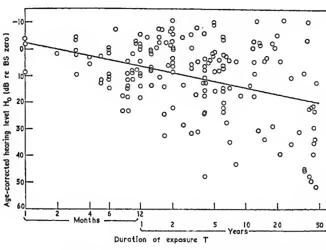
noise exposure measure. This is described in Appendix 11, in which it is shown that the function $E_{A2} = L_{A2} + 10 \log (T/T_0)$, termed *A-weighted noise immission level*, is directly related to the noise-induced hearing loss H.



10.7 To show the similarity between age-corrected hearing levels relative to controls, against log exposure duration with noise level as parameter, and against noise level with duration as parameter. Frequency 4 kHz, 581 subjects.

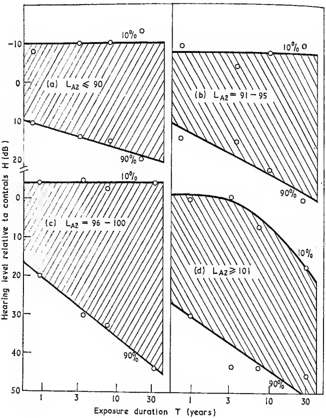
2.2.2 *Preliminary analysis of scatter*

A general impression of the scatter of hearing levels can be gained from the example illustrated in Fig. 10.8, which shows the results for the 172 subjects falling within the noise band $L_{A2} = 95–99$. The retention of unimpaired hearing by a fraction of the subjects after prolonged exposure is evident; it has the corollary that the dispersion increases with the exposure. Corresponding diagrams for the other 3 noise bands (not illustrated) are similar in that the data fan out with exposure duration, and range between the unimpaired and something of the order twice the mean. This is illustrated in Figs. 10.9 (a) — (d) which show the upper and lower deciles within the groups whose means are plotted in Fig. 10.7. Except for the highest noise band it is noticeable how the upper decile remains constant. There is some instability in the decile values due to the comparatively small numbers of subjects (of the order 30) in each cell and the next step was to look for systematic trends on the basis of which the statistical distributions might be smoothed.

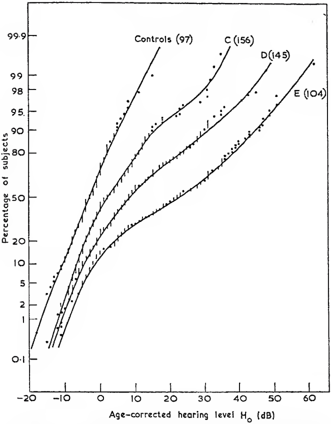


10.8 An example of the scatter of measured hearing levels. Frequency 4 kHz, 172 subjects; noise level L_{A2} 95–99.

The procedure was suggested by the observation in Section 1.2 (iii), that equal noise immission levels E_{A2} produce equal mean values of



10.9 Showing how the hearing level of the upper decile (i.e. ears resistant to noise-induced hearing loss) remains little affected by increased exposure duration, while the lower decile (susceptible ears) deteriorates rapidly. Frequency 4 kHz.



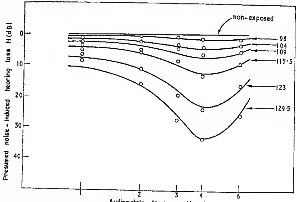
10.10 Cumulative distributions of hearing levels of groups classified by noise immission level (NIL). Frequency 4 kHz; groups C D and E are in ascending order of NIL. Figures in brackets are number of subjects in each group.

H. By pooling the data from cells for which the mean noise immission levels were approximately equal, a smaller number of larger groups was compiled and the cumulative distributions of hearing levels H_O within these groups* are as shown in Fig. 10.10. To these groups have

* The distributions for groups A (62) and B (96) are omitted to avoid complicating the figure.

been added the 97 controls, the distribution of whose 4 kHz hearing levels is seen to be nearly Gaussian (a straight line on the probability-integral scale used as ordinate). It is now seen that the increased scatter of the exposed groups (represented by the progressively less steep average slope of the distributions) is also accompanied by a distortion of the Gaussian distribution in what appears to be a highly systematic way, the point of inflexion of the lines moving from top left towards bottom right with increasing noise immission level. Further evidence of an ordered structure governing the distributions appeared later when corresponding results for other frequencies were examined. This is described in Section 2.3.2 below.

The mean audiograms for the larger groups sorted into noise immission level bands are shown in Fig. 10.11, expressed relative to the controls. Presbycusis correction has been applied, so that these results summarised, at this stage, the mean trend of the presumed noise-induced hearing loss component. The parameter is mean noise immission level for the group, E_{A_2}, in decibels relative to $L_{A_2} = 0$ dB(A) for 1 month. The data points are shown approximated by a set of similar curves differing only by a multiplying factor on the ordinate, though this representation differs from our final one.



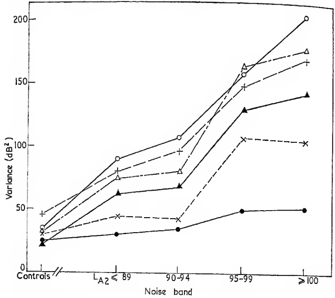
10.11 Intermediate summary of values of presumed noise-induced hearing loss at the audiometric frequencies. Parameter is noise immission level (value opposite each curve).
Noise immission level $E_{A_2} = L_{A_2} + 10 \log (T/1 \text{ month})$.

TABLE 10.6
Variance of hearing levels within different noise groups

Audiometric frequency (kHz)	Variance in group (dB^2)					Variance
	Controls	A*	B*	C*	D*	
	n = 97	118	130	172	161	
1	24	31	36	49	53	$\sigma_S^2 + \sigma_O^2$
2	30	46	42	107	105	,,
3	31	74	80	164	177	,,
4	34	89	108	157	205	,,
6	45	80	96	147	169	,,
Mean	36·7	81	94·7	156·0	183·7	$\sigma_S^2 + \sigma_O^2$
3/4/6 (hearing levels averaged)	23	62	68	129	143	$\sigma_S^2 + \frac{1}{3}\sigma_O^2$
By difference	13·7	19·0	26·7	27·0	40·7	$\frac{2}{3}\sigma_O^2$
Estimated component	20	28	32	53	63	σ_O^2
,,	17	53	63	103	121	σ_S^2

* The variance in these cases is the regression variance about a straight line fitted to H_O and log (T/T_O).
A, B, C and D are the groups in the L_{A2} noise bands $\leqslant 89$, 90 — 94, 95 — 99 and $\geqslant 100$ respectively.

Numerical values for the variance are provided in Table 10.6. For this purpose the 4-noise-band linear regression analysis, with presbycusis correction, was run at 1, 2, 3, 4 and 6 kHz, together with the average over 3, 4 and 6 kHz, and the 97 controls are included. Fig. 10.12 shows the results for individual frequencies; for the exposed groups the ordinate is the variance about the regression line of H_O against exposure duration. The values of variance given here contain intersubject variance σ_S^2 and random error variance σ_O^2. Further discussion of the latter component is given in Appendix 12 where the same term appears as the principal component of the test/retest variance in serial audiometry. Certain important features of σ_S^2 and σ_O^2 can, however, be deduced directly from Table 10.6. Thus, comparing the average of the variances for 3, 4 and 6 kHz with the



10.12 Variance of hearing levels of control subjects and of various noise groups. For the latter the variance is that about the regression line of hearing level against exposure duration. The variance depends on frequency and increases with noise level. Symbols: 1 kHz, •; 2 kHz, ×; 3 kHz, △; 4 kHz, o; 6 kHz, +; Mean of 3, 4 and 6 kHz, ▲.

variance for the average hearing level at these three frequencies, it is clear that the former is considerably greater than the latter. On theoretical grounds the difference should be approximately $(2/3)\sigma_0^2$. The relation would be exact only if σ_S^2 and σ_0^2 were independent of frequency and if there were no correlation between a person's hearing level at different frequencies. Notwithstanding this approximation, a glance at Table 10.6 is sufficient to show that both σ_S^2 and σ_0^2 increase markedly with exposure noise level. In the case of σ_S^2 this can clearly be attributed to the variations of noise susceptibility between individuals, though the discontinuity between the small value for controls

and the next-lowest value for Group A is rather abrupt. There is no obvious explanation, however, of why the random error should also vary unless it is evidence of residual tinnitus due to the previous day's noise exposure, or a general property of impaired ears. However, the evidence from repeated audiograms in the serial study described in Appendix 12 reveals a similar increase in the residual variance as noise level increases, so that we believe the phenomenon to be real. An attitudinal factor influencing noise-deafened subjects' performance at the audiometric test cannot be entirely discounted but it seems hardly likely to be consistent enough to explain the results obtained, nor does it appear to occur in low frequency results, e.g. 1 kHz.

2.3 STAGE (iii) — 759 SUBJECTS

2.3.1 *Establishment of median hearing loss trend*

The 20 cell (4L × 5T) analysis was rerun for the total group of subjects (now 759), and for each audiometric frequency from 0·5 to 6 kHz, with the standard presbycusis correction (m = 1) subtracted from the measured hearing levels. The programme was modified so that, within each cell, the subjects were arranged in order of ascending age-corrected hearing level H_0 and the left- and right-ear mean was printed out. This enabled cumulative distribution curves to be plotted directly and the value of the median in each cell to be determined.

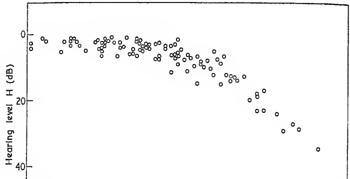
When these medians were plotted against the average noise immission level for the group, it was found that the resulting curves were basically similar for each frequency: at first a very slow growth of H_0 with E_{A2}, followed by an accelerating trend and, at the upper end of the noise immission level scale, a tendency to saturate. There was, however, a marked difference of the positions along the E_{A2} scale at which corresponding values of H occurred for the different frequencies; this would be expected from the characteristic audiograms of noise-induced deafness, i.e. the 4 kHz dip, as in Fig. 10.11. What was not expected, but which was clearly suggested by these curves, was that their shape was remarkably similar in such a way that the results for all frequencies could be collapsed on to a single curve by suitably shifting the origin of the E_{A2} scale for each frequency. These axis shifts were decided by trial and error, with the result shown in Table 10.7. The shifts are arbitrarily pegged to zero at 4 kHz.

TABLE 10.7
Normalising shifts, in decibels, for hearing loss trend curves at different frequencies

Frequency (kHz)	1	2	3	4	6
Axis shift ΔE_A (dB)	14	7·5	2	0	3

Due to the small values of H at 500 Hz even for the highest noise immission level, it was difficult to determine an axis shift with the same assurance but a trial value of 17.5 dB was assigned. This was found to be consistent with the further analysis described in Section 2.3.2 and has been adopted.

After this process the 20-cell medians for 1, 2, 3, 4 and 6 kHz appear as illustrated in Fig. 10.13. The abscissa here is a normalised form of the noise immission level E′, equal to $E_{A2} + \Delta E_A$ (see Table 10.7). The nature of the variation of H with E′ seen in Fig. 10.13



10.13 Showing how the noise-induced component of hearing loss grows in an essentially similar manner at different frequencies, and that it can be represented by a single curve on a scale of noise immission level whose zero is adjusted, by trial and error, according to frequency. Hearing levels were derived from both ears of 759 subjects at 5 frequencies (1, 2, 3, 4 and 6 kHz).

resembles that, often met with in biological growth functions, with the general differential equation $y' = ky^n(y_\infty - y)^m$, where y_∞ is the ultimate "size" attained. It was found that the simplest form of this function (with $n = m = 1$) was adequate to fit the data on Fig. 10.13, the mathematical expression being

$$H = a\left\{1 + \tanh\frac{E' - E_O}{\mu}\right\}$$

Trial values were $a \sim 30$, $\mu \sim 15$, $E_O \sim 128$.

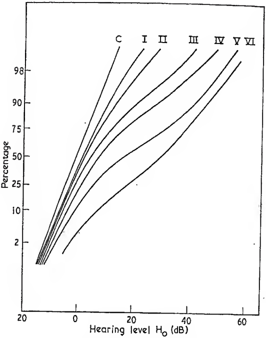
This function has evident logical advantages over the linear regression discussed in Sections 2.1 and 2.2: it is zero for zero immission and tends to a limiting value 2a which, save for the added hearing loss due to age, accords with the fact that a person's hearing level cannot increase beyond the point at which no hearing remains (see Section 6).

The finalisation of the constants a, E_O and μ was deferred until the next stage of the analysis was completed (see Section 2.3.2).

2.3.2 *Establishment of centile hearing loss trends*

In estimating the median values within cells, as discussed above, it was noticed that the shape of the cumulative distribution curves persistently exhibited the tendency illustrated in Fig. 10.10 as the noise immission level increased. Moreover, it was found that the shape of the curve, like the position of the median described above, was similar for groups of data at different frequencies if they were compared at noise immission levels shifted according to frequency. Due to the instability of some of the distributions for cells with rather small numbers of subjects, 7 larger groups were composed (including the 97 controls) and the cumulative distributions for each, at each audiometric frequency, were drawn out as transparencies. Matching of the shapes was found to occur surprisingly closely when shifts identical to those given in Table 10.7 were applied. In this way it was possible to construct master cumulative distribution curves which summarised all the data. These are shown in Fig. 10.14, in which each group is an assemblage of the results for various noise immission level bands and frequencies, and from the Figure, the various centile hearing levels could be estimated in terms of the frequency-normalised noise immission level $E' = E_{A2} + \Delta E_A$ (which is the parameter attached to each group).

The next step was to plot the values of the age-corrected hearing level H, for various centiles of the population, against E′. They



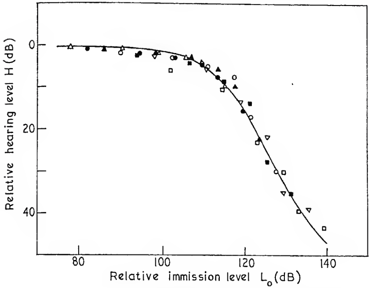
10.14 Cumulative distribution of hearing levels of groups classified by frequency-normalised noise-immission level. Classification:

Group and symbol		No. of data	Normalised noise-immission level $E_{A8} + \Delta E_A$
Controls	C	970	—
Noise-exposed	I	1742	90
,, ,,	II	2902	102·5
,, ,,	III	1676	111
,, ,,	IV	610	117·5
,, ,,	V	458	121·5
,, ,,	VI	202	127·5

were read directly from Fig. 10.14 relative to the corresponding value for the control group.

It was now observed that if the values for various centiles were plotted against E′, with a further scale shift depending on the value of the centile, the data points again collapsed fairly well on to a single curve.

This is illustrated in Fig. 10.15. To achieve this result the data for the 2nd centile were shifted 12 dB relative to the median, the 98th centile −12 dB, and the remaining points by amounts proportioned



10.15 Showing how the relative hearing level of various centiles can be represented by a single curve on a scale of frequency-normalised noise-immission level whose zero is adjusted according to the centile. The zero adjustment is proportional to the distance from the median as measured along the decibel scale for the non-exposed control group. The centile values selected here correspond to equal decibel intervals for a Gaussian distribution. The solid line represents the equation

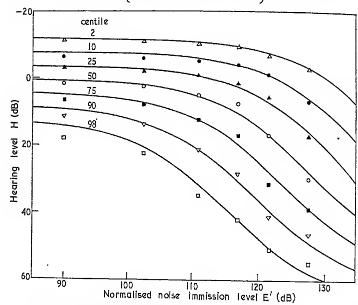
$$H = 27{\cdot}5 \left\{(1 + \tanh \frac{L_0 - 127}{15}\right\}$$

Number of original data 7590 (759 subjects × 2 ears × 5 frequencies). Symbols for centiles: 2, △; 10, ●; 25, ▲; 50, ○; 75, ■; 90, ▽; 98, □.

simply by the Gaussian distribution of the control group (C of Fig. 10.14), Due to the axis-shifting process the abscissa L_O of Fig. 10.15 is a relative scale, the numerical values being correct only for the median data at 4 kHz. The median points in Fig. 10.15 repeat, in summarised form, the same data as are shown in Fig. 10.13, and it next appeared that a unique relation between H and normalised noise immission level would express all the results, inclusive of the medians and various centiles.

Adjustments were made to the coefficients in the equation given in Section 2.3.1 so as to permit the statistical distribution as well as the medians to be fairly closely represented by the same curve, i.e. Fig. 10.15 was used to finalise the coefficients and to establish the relation:

$$H = 27{\cdot}5\left\{1 + \tanh\left(E_A + u_p - \lambda_j\right)/15\right\} + u_p$$



10.16 Showing the age-corrected hearing levels (relative to controls) for various centiles of 6 groups classified by frequency-normalised noise-immission level. The curves are parallel to that shown in Fig. 10.15, each being displaced 4 dB horizontally and vertically from its neighbour. Beyond the left-hand margin the curves fit closely to the centiles of the control group (not shown, but see Fig. 10.14).

with the values of u_p and λ_i as given in Tables 10.1 and 10.2.

How well this unified function represents the experimental data is illustrated in Fig. 10.16 in which the hearing loss for each centile is plotted in its correct vertical position, on the scale of frequency-normalised noise immission level E′. The data points refer to the same groups as on Fig. 10.14. It would be possible to draw slightly different curves through each set of points which would be in closer accord with these points but only at the expense of complicating the expression of the results since, as drawn, all these curves are identical, separated simply by diagonal displacement. Fortunately the only discrepancy of any important magnitude occurs at the left hand of Fig. 10.16 where the 95th and 98th centiles lie a little off the curves; this however is not a region of practical importance from the standpoint of noise-induced deafness.

Referring back to the original data, the scatter of a sample from which is illustrated in Fig. 10.8, there seems to be no justification for departing from the mathematically economical result.

It is not to be inferred that a particular ear would follow the course of one of the curves of Fig. 10.16, which must be interpreted as a statistical statement. It is, at the same time, interesting to note that the Figure implies a small percentage of "tough" ears (upper curve) and a small percentage of "tender" ears (lower curve) which respond to increasing noise immission in an essentially similar way save only for a resistance factor which appears as a constant shift on the logarithmic abscissa. The characteristic distortion of the statistical distributions of hearing levels can now be seen simply as a reflection of the unequal vertical intervals between the curves; the same thing would happen with any such set of parallel sigmoid curves staggered diagonally.

3. Estimating the risk of hearing loss due to noise

An algebraic expression for predicting the noise-induced component of hearing loss has been given in Section 1.3. This lends itself conveniently to a graphical presentation, in the form of Fig. 10.17.

The manner of using this nomogram in its simplest mode is as follows:

		Example
Step 1	Determine noise level L_A and period of exposure T (years).	96 dB(A); 25 years

Step 2	Calculate $L_A + 10 \log T = E_A$ and enter appropriate curve in upper half of nomogram.	$96 + 10 \log 25 = 110$
Step 3	Select audiometric frequency and locate intersection with the appropriate E_A curve.	2000 Hz; Point A
Step 4	Descend vertically from this intersection into the lower half of the nomogram.	Line AB
Step 5	Select centile of interest, p, and locate intersection of the vertical from Step 4 with the appropriate curve.	10%; Point C
Step 6	Read out level of this intersection on left-hand lower vertical scale. This is H, the presumed noise-induced hearing loss that would be exceeded only by the selected percentage of persons.	32 dB
Step 7	Add age correction according to Table 10.3 (Section 1.3). *Note:* For general predictive purposes it may be adequate to take the age N equal to T + 20.	$0{\cdot}0060 \times 25^2$ Result: 36 dB

The result of Step 7 is H′, the hearing level that would be exceeded only by the selected percentage of persons provided that they were free from all sources of hearing impairment other than the noise exposure assumed. The results obtained by this procedure are naturally somewhat smaller than those given by other surveys in some of which less rigorous exclusion criteria have been applied in respect of extraneous hearing impairment factors. This is discussed further in Appendix 15.

For the estimation of risk the nomogram is used in a slightly different way. Steps 1–4 are as before but one then proceeds as follows:

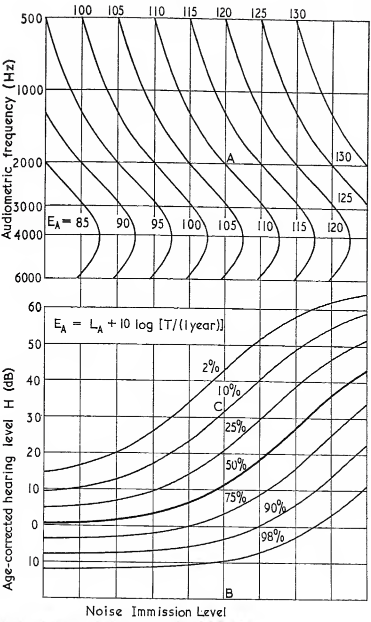
Step 5A Select hearing level criterion H′.

Step 6A Subtract age correction appropriate to the duration assumed, and enter the lower part of the nomogram at the resulting hearing level.

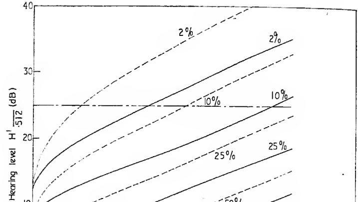
Step 7A Locate the intersection of the level with the vertical from Step 4.

Step 8 Read centile p by interpolation.

10.17 Nomographic chart relating audiometric frequency, noise level, exposure time, percentage of the exposed persons, and hearing level (exclusive of presbycusis) relative to 20-year old non-exposed controls.


100 105 110 115 120 125 130
500
1000
2000
3000
4000
6000
Audiometric frequency (Hz)
A
130
125
$E_A = 85$
90
95
100
105
110
115
120
60
50
40
30
20
10
0
10
$E_A = L_A + 10 \log [T/(1 \text{year})]$
2%
10%
C
25%
50%
75%
90%
98%
Age-corrected hearing level H (dB)
B
Noise Immission Level

The value of p estimates the percentage of persons whose hearing level will exceed the assumed criterion level H′. It therefore slightly over-estimates the percentage at risk due to the noise exposure, since some smaller percentage, say p′, would have exceeded the criterion level in the absence of noise in any case as a result of natural ageing. The estimation of p′ requires a study of the distribution of presbycutic hearing loss in non-noise-exposed populations. As already mentioned, there are numerous published investigations from which the reader may select. The formal definition of risk is usually taken to be p − p′, but until such time as presbycusis data become standardised we prefer the more conservative definition of risk given by p. Except for mild noise exposures, or for predictions to advanced age, the difference is in any case slight.



10.18 Example of "risk curves" for noise and age combined, in subjects free from other impairments. The ordinate is the average hearing level at 0·5, 1 and 2 kHz. The AAOO "beginning mild impairment" fence at 25 dB (ISO) is shown. Each pair of curves signifies the level of the occupational noise: 90 dB(A), continuous line; 95 dB(A), interrupted line.

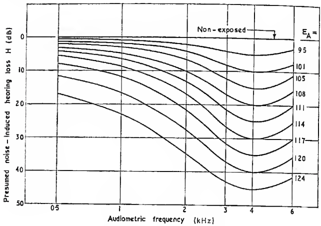
In practice, the hearing level criterion required at Step 5A will often be in the form of an average at several audiometric frequencies. For example, the American Academy of Opththalmology and Otolaryngology (AAOO) (3) specifies a mean hearing level at 500, 1000 and 2000 Hz of 25 dB (relative to ISO datum) as the "beginning of slight impairment" for the understanding of spoken English. To calculate risk in such cases, it is necessary to proceed in the manner of Steps 1–7, at each frequency in question and for a range of selected centiles at Step 5. The mean hearing level can then be plotted against the centile and the value of the latter which corresponds to the given criterion read off the curve. This procedure can easily be repeated for various combinations of noise level and duration, and the result shown as a set of risk curves.

Such a set of curves is shown in Fig. 10.18, in which the hearing level has been taken as the mean at 0·5, 1 and 2 kHz. The examples shown are for $L_A = 90$ and 95 dB(A), and for the range of exposure durations from 0 to 40 years. The presbycusis component has been added in accordance with the Note in Step 7 above, i.e. the results apply to persons entering noisy employment at the age of 20. The criterion of maximum acceptable hearing level may be set by the user as a horizontal "fence" on the diagram. Bearing in mind that this prediction chart takes no account of adventitious hearing losses such as would be likely to accrue from causes other than noise and age, it would be reasonable to draw the fence as a line sloping downwards to the right, starting (for example) from the 25 dB level recommended by AAOO or lower. We make no specific recommendations about this downward adjustment, but evidence from other surveys of the incidence type, such as that by Baughn (4), suggests that it should be substantial.

Whilst the construction of diagrams such as Fig. 10.18 is straightforward, a simpler method is available which yields a close approximation. This depends on the fact that the centile distribution (lower half of Fig. 10.17) is uniquely determined by the median hearing level. We present first the median "audiograms" of Fig. 10.19, calculated from Fig. 10.17. The curves* shown are for steps of 5 dB at 4 kHz and

*These curves may be compared with those on Fig. 10.11 which were derived at an intermediate stage of the analysis. The parameter on Fig. 10.11 is $E_{A2} = L_{A2} + 10 \log (T/1 \text{ month})$, so that $E_{A2} \sim E_A + 14.5$. Comparison shows that although the curves were derived on different principles, and in one case from only a fraction of the raw data, the practical result is little different.

the parameter is noise immission level $E_A = L_A + 10 \log (T/1 \text{ year})$. Using Fig. 10.19, the median presumed noise-induced hearing loss may be read off for any frequency, or any desired combination of frequencies. This value should then be entered along the "median" scale of Fig. 10.20 and traced parallel to the curves as far as the centile of interest. The required hearing level is then obtained by reading off the vertical scale and adding the presbycusis correction according to Table 10.3.



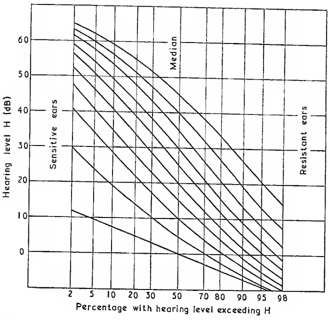
10.19 The component of hearing loss due to noise alone is shown for the median subject in the form of audiograms, illustrating the 4 kHz dip. The parameter is noise immission level.

4. Effect of spectral distribution on the noise-induced audiogram

4.1 CLASSIFICATION OF SPECTRA

The noise spectra encountered in this investigation covered a very wide range, both in intensity and frequency distribution. In the foregoing analysis, the level has been implicitly assumed to be the sole factor governing noise-induced hearing effects but it is known from auditory fatigue studies that the maximum threshold shift occurs at

a frequency related to the spectral distribution of the stimulus. For comparatively narrow bands of noise, it is reported that the maximum occurs at an audiometric frequency about half an octave higher. Whilst such specificity would not perhaps be expected for broad-band excitation, there might be some signs of a systematic difference in the shape of the noise-induced audiogram as between rising and falling spectra. An analysis of the results classified by spectral distribution might also reveal something about the weighting curve required to generalise the predictions of hearing loss. In the foregoing analysis the A-weighting was heavily relied on from the outset, following indications from the current literature and trends in the sphere of international standardisation. It was shown to account better for the observed hearing levels than NR or the value L_{2000}, but these options by no means exhaust the possibilities.



10.20 Diagram for use in constructing risk tables.

In the presence of so many different noise spectra exhibiting all manner of irregularities a classification into rising and falling could only be done on a somewhat arbitrary basis. A rapid inspection showed that the levels L_{63} and L_{125} rarely represented a significant contribution. The same was true of L_{8000}, which was almost invariably much lower than L_{4000}. It was also observed that the value of L_{1000} was frequently half way between L_{500} and L_{2000} within 1 or 2 dB but there were certain large exceptions. Two definitions of spectrum slope were therefore adopted:

$$S_1 = \tfrac{1}{2}(L_{250} + L_{500}) - \tfrac{1}{2}(L_{2000} + L_{4000})$$

and $$S_2 = \tfrac{1}{3}(L_{250} + L_{500} + L_{1000}) - \tfrac{1}{2}(L_{2000} + L_{4000})$$

After carrying through the first of the analyses described below it was evident that any distinction between the results of classification according to S_1 and S_2 was of negligible account, and further treatments were confined to S_1.

The 759 subject data were computer sorted into ascending order of S (which in case of S_1 ranged from −13 to +15) and the list grouped in 6 bands of S each 5 dB wide. Within each group the subjects were sorted into 4 noise level bands, in order that comparisons of the mean audiograms for different spectrum slopes should not be biased by differences in absolute magnitude.

4.2 RESULTS

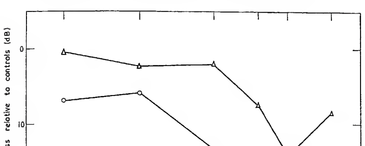
The result of grouping the 759 subjects according to a two-way classification by S_1 and L_{A2} was as shown in Table 10.8. 4 subjects with L_{A2} less than 80 dB(A) are not included. The Table serves to

TABLE 10.8

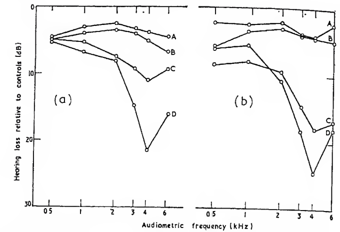
Distribution of subjects within cells classified by spectrum slope (S_1) and noise level (L_{A2})

S_1 band	L_{A2} band				
	A	B	C	D	E
	80–89	90–94	95–99	100–109	⩾110
1 −13 to − 8	—	—	—	2	12
2 − 7·5 to − 3	5	29	48	59	1
3 − 2·5 to + 2	92	91	105	60	4
4 + 2·5 to + 7	68	29	53	25	—
5 + 7·5 to +12	6	15	14	9	—
6 +12·5 to +17	—	28	—	—	—

show that there was a tendency for high S-values (i.e. rising spectra) to be associated with high absolute noise levels, and low values (falling spectra) with the quieter environments; although ours was not garnered as either a random or a deliberately representative sample of industrial noises this seems to be the general rule. Unfortunately it hinders symmetrical comparisons between columns and rows of the Table, as does the fact that the cells in the 1st, 2nd, 5th and 6th rows (which would best show up the spectrum-dependent effect, if any) contain relatively few subjects. A direct comparison between the mean audiograms for cells 1E and 6B is, however, symptomatic of the results of more elaborate analysis and is shown in Fig. 10.21. The hearing levels are expressed relative to the non-noise-exposed controls. Both cell means exhibit the classical 4 kHz dip and there is no visible sign of the dip being higher in frequency for group 1E than for group 6B. The difference in magnitude of the hearing losses is due to the inequality of the absolute noise levels.



10.21 Comparison of audiograms for small groups with extreme spectrum slopes. Symbols: cell 1E (rising spectra), o; cell 6B (falling spectra), Δ.



10.22 Mean audiograms for groups classified by spectrum slope and noise level L_{A2}. (a) for rising spectra (S_1 band $-7{\cdot}5$ to $+2$); (b) for falling spectra (S_1 band $+2{\cdot}5$ to $+12$). The parameter (A, B, C, D) is the noise level in the L_{A2} bands.

A more equitable comparison is provided by Fig. 10.22. Here noise band E has been eliminated as it is not represented at all among the falling spectra; also the 1st and 6th S-bands have been omitted. The remaining S-bands have been amalgamated into two, with S_1 ranging from $-7{\cdot}5$ to $+2$ and from $+2{\cdot}5$ to $+12$ respectively, as in Table 10.9. Fig. 10.22 shows, again, no marked evidence of the audiogram shape depending on the spectrum slope; indeed the grand average results are remarkably similar in form as seen in Fig. 10.23, where the ordinate is the unweighted average over the four L_{A2} bands A—D.

TABLE 10.9

Distribution of subjects into larger S_1-groups

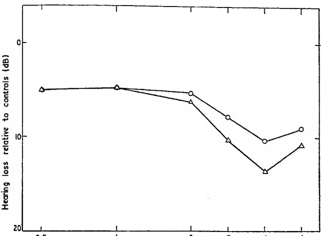
S_1 band	L_{A2} band			
	A	B	C	D
$-7{\cdot}5$ to $+2$	97	120	153	119
$+2{\cdot}5$ to $+12$	74	44	67	34

To summarise the evidence, there appears to be no difference between the shape of the audiogram when the following comparisons are made:

(a) Spectrum rising 4 dB/octave (12 subjects)
and spectrum falling 5 dB/octave (28 subjects)

(b) Spectrum rising on average 1 dB/octave (489 subjects)
and spectrum falling on average 2·5 dB/octave (219 subjects)

Whether effects would show up with still more strongly falling or rising spectra is conjectural but it seems safe to conclude, with considerable confidence within the range of spectrum slopes from say +5 to −5 dB/octave, that the average noise-induced audiogram is for all practical purposes the same.



10.23 Showing that the shape of the average audiogram for large groups does not depend on the frequency distribution of the noise. Note a certain difference of magnitude. The ordinate is the unweighted average value of H over four L_{A2} noise bands ($L_{A2} < 110$). Symbols: for rising spectra ($S_1 = -7·5$ to $+2$, number of subjects 489), o; for falling spectra ($S_1 = +2·5$ to $+12$, number of subjects 219), Δ.

This is indeed a fortunate experimental observation, for otherwise it would be necessary to sophisticate the prediction formulae and nomograms, as well as requiring a frequency analysis of the noise instead of a simple overall measurement.

4.3 OPTIMUM FREQUENCY WEIGHTING

It is noticeable on Figs. 10.22 and 10.23 that the hearing loss is slightly greater in magnitude for subjects in the "falling spectra" class compared with those exposed to rising spectra, when the L_{A2} values are equal. Inspection of the data showed that exposure durations were about equally distributed in the two classes and would not account for the difference.

It seemed possible, indeed not unlikely, that the reason lay in the somewhat arbitrary selection of A-weighting to express the noise levels. To determine whether a modification of the frequency weighting would account for the difference, two methods were used, as described in the following sections.

4.3.1 *Derivation of frequency weighting from mean audiograms*

This method is based on the proposition that, whereas the two curves of Fig. 10.23 correspond to almost identical mean values of L_{A2}, the groups might have been so composed that the mean audiograms coincided. The mean value of L_{A2} for the falling spectra would then have been lower than that for the rising spectra, but possibly the same for some other weighting. To estimate the difference, the data for 3, 4 and 6 kHz (averaged) from Fig. 10.22 were replotted against mean noise level for the groups (A—D) and the stagger between the respective sets of data points was estimated at 3·0 dB(A).

Now, by assuming the mean octave band spectrum shape for each class ($S_1 = -7{\cdot}5$ to $+2$ and $+2{\cdot}5$ to $+12$) to have the mean slope for the class, and by applying the A-weighting to the octave band levels, the weighted sound level in dB(A) was calculated and the two spectra adjusted in absolute level so that they differed by 3 dB(A).

Other weightings were then applied to these adjusted mean spectra in order to find which one would equate them. Those tried were B-weighting, unweighted (overall sound pressure level), and an artificial weighting A′ in which the response (referred to 1 kHz) was half the value for A-weighting. The result was as follows.

Table 10.10 suggests that the A′-weighting does not go quite far

TABLE 10.10
Search for a frequency weighting to compare equinoxious noises correctly

	dB re arbitrary datum			
	A-weighting	A′-weighting	B-weighting	Flat
Rising spectrum	3·0	3·0	2·4	3·2
Falling spectrum	0	1·6	2·7	3·9

enough, B slightly overcompensates and "flat" goes too far. This arithmetic is necessarily tentative since no actual spectrum shape corresponded to either of the average shapes assumed, but similar calculations assuming spectra with twice the slope yielded roughly the same conclusion as Table 10.10, so it seems correct to conclude that the A-weighting tends to be too severe, presumably because of the low-frequency cut.

4.3.2. *Confirmation by direct calculation*

The octave band noise levels for each of the 759 subjects were used to calculate sound levels L_A, L_B and L_{flat} with the A, B and "flat" weightings respectively. Note that L_A is closely related to, but not identical with, L_{A2} of the previous analysis. New tables analogous to Table 10.8 were drawn up (using the same divisions of S_1 as before) and the mean audiograms within cells calculated. In the nature of this process, there were a considerable number of interchanges of subjects between corresponding cells and in comparing the means of such cells one is therefore not comparing exactly the same group of individuals.

Fortunately the numbers involved are reasonably large (see, for example, Table 10.9). In Table 10.11 below, a, b, c and d represent the four noise bands (in ascending order) into which the weighted sound levels were divided. The Table entries are for the mean hearing level at 3, 4 and 6 kHz, and each is the difference between the mean value for the group with falling spectra and that with rising spectra. The corresponding value from Fig. 10.23 for L_{A2} classification (average of all bands a—d) is 2·4, not quite the same as the value for "abcd: A-weighting" from Table 10.11, which is 3.5 dB.

TABLE 10.11

Difference between mean hearing levels (at 3, 4 and 6 kHz) for groups exposed to falling and rising spectra respectively, when classified into corresponding bands of weighted sound level, for different weightings

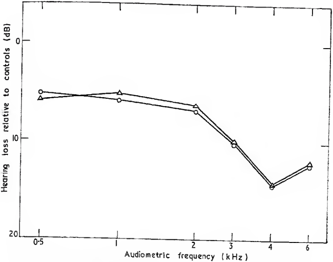
Noise bands included in average	Difference (dB) when classified by weighting:		
	A	B	Flat
a b c d	3·5	−0·3	−0·4
a b c	3·7	1·4	−0·4
b c d	2·6	−1·1	0·5

One might have expected the values to be progressive from A through B to "flat" but the sequence is interrupted in the third row (bcd) no doubt due to sampling errors. Nevertheless, the result seems to show fairly clearly that the B-weighting more nearly equates hearing losses than does A, and that "flat" weighting somewhat overcompensates. This exactly confirms Section 4.3.1 above. Fig. 10.24 shows the actual mean audiograms for the B-weighting classification (mean of all noise bands) and is to be compared directly with Fig. 10.23.

4.3.3 *Conclusion*

The evidence from Sections 4.3.1 and 4.3.2 that the A-weighting is excessive is rather persuasive but it has to be set against the consideration that the A-weighting has attained a very wide usage in many fields of applied acoustics whilst B-weighting has practically lapsed into desuetude; also the fact that the practical consequence of this choice in terms of error is small. We have seen that, relative to the grand average noise spectrum, the use of A-weighting to estimate noise-induced hearing loss due to markedly rising and falling spectra respectively implies an error of not more than the order ±2 dB. Such deviations can surely be disregarded in all practical cases; rarely would noise immission level be known or forecast to this accuracy and even if it were the error of interpretation in terms of risk would be unimportant.

We make no apology, therefore, for concluding that these results justify the use of sound level A for rating the hazard of a wide range of industrial noises.



10.24 Showing that groups exposed to falling and rising noise spectra which are classified by sound level B exhibit practically identical mean audiograms. The ordinate is the unweighted average value of H over four L_B noise bands ($L_B < 110$). Symbols: for rising spectra ($S_1 = -7{\cdot}5$ to $+2$, number of subjects 493), o; for falling spectra ($S_1 = +2{\cdot}5$ to $+12$, number of subjects 218), Δ.

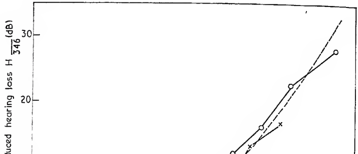
5. Comparison of the noise-induced hearing loss in males and females

Of the 759 subjects in the retrospective survey, 422 were male and 337 female. They have hitherto been considered as an ensemble, on the grounds that the elucidation of the intrinsic relations between noise exposure and hearing loss is facilitated in the presence of larger numbers of data, and that any sex-linked differences are likely to be of degree rather than of a fundamental kind. Having arrived at the concise formulation given in Section 1.3 it was a simple matter to explore the difference on a basis of sex.

For this purpose two lists were prepared by computer, one for males and the other for females. In each, the subjects were ranked from low to high in order of noise immission level E_{A2}, along with the

age-corrected hearing level H averaged over both ears and over the three frequencies 3, 4 and 6 kHz. Each list was then divided into bands and the average of E_{A2} and H calculated for each band. The boundaries were arbitrarily selected so as to embrace approximately equal ranges of E_{A2}. There are between 30 and 90 males in each average and between 24 and 72 women. The resulting average values are plotted in Fig. 10.25.

It is clear that there is a persistent, though not very large, difference in the direction of female ears being more resistant to noise. The tendency appears to be greatest for moderate noise immission levels and to be diminishing at the upper end of the range. We had no cases of females exposed to noise immission levels greater than 127 dB (relative to 0 dB(A) for 1 month), whereas the exposures for males



10.25 Comparison of presumed noise-indu. ɔd hearing loss (average of 3, 4 and 6 kHz) for males and females. Symb. :: 422 males, o; 337 females, ×; mean calculated from formula (see text), interrupted line.

ranged as high as 148. Within each list the data were fairly uniformly distributed over the whole of the respective immission level range.

The Figure also shows the value for the composite group of 759 derived from the equation in Section 1.3. To effect a correct comparison, the dotted curve shown is the prediction of the mean rather than of the median, since the data points for males and females were computed in this form. The dotted line is thus very slightly displaced in relation to the 50th centile curve in the lower half of Fig. 10.17. To obtain it we calculated the mean of the distributions represented by vertical cross-sections in the latter figure, for the three frequencies concerned. The mean exceeds the median by amounts varying from zero to 1·4 dB.

The relative resistance of female ears has been observed by other research workers and is discussed further in Appendix 15.

The results displayed in Fig. 10.25 suggest a further axis shift, for normalising male and female results, on the same principle as discussed in Sections 2.3.1 and 2.3.2 for normalising the results for different frequencies and different centiles. It is evident that a relative horizontal translation of the male and female curves of some 3 dB along the noise immission scale will bring them practically into coincidence, bearing in mind that each data point represents some 30–90 individuals with a fairly large intersubject dispersion (see Table 10.6). For purposes of refined comparisons we therefore suggest to modify the values of λ in Table 10.1 as follows:

for males:	subtract 1·5 dB
for females:	add 1·5 dB

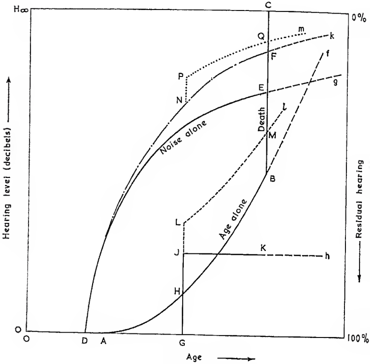
The corresponding adjustments may be made when using Fig. 10.17, the rule being to enter the diagram 1·5 dB to the right of the indicated position for male predictions, and 1·5 dB to the left for females.

It has been observed by other workers that the presbycutic characteristics of the hearing in men and women exhibit certain differences in the same direction as our findings. This is not the explanation of the separation of the curves on Fig. 10.25. However, it may be that the final step in obtaining H' from H, i.e. adding the term C_1 $(N-20)^2$, could take account of this distinction by assigning slightly different values of C_1 to the two sexes. In the present state of knowledge, as mentioned in Section 1.2, we did not feel able to assign any numerical values.

6. On mathematical modelling

As will be evident from Fig. 10.17 and its algebraic equivalent, the relationships between the cause and effect variables in hearing loss come close to being represented by a mathematical model of remarkably compact form and extreme economy of parameters.

Some authors are content to let experimental data speak for themselves; a few adopt low-order curve-fitting as an aid to reading out the results and using them for comparative purposes. But the gap between this and the quest for a truly-ordered structure expressed in



10.26 Diagrammatic course of the hearing loss under separate and combined influences.

mathematical terms is a large one. The natural philosophy to which we subscribe is that things, in their nature, must be so ordered, a view which is shared by Baughn (5) amongst others.

To illuminate the properties of this structure one must successively approximate using, at each step, mathematical forms which at least possess qualities that do not contradict natural law, and which are faithful to such maxims as "nature abhors sharp corners".

In this sense, as well as in the practical sense, we are content with Fig. 10.17 of this Report save for one feature. This concerns the additivity of partial hearing losses from independent causes, and the terminal behaviour of the hearing loss function for high noise immission levels. We have taken the immission and presbycusis components to be arithmetically additive, but since each on its own (given sufficient noise or longevity) could ultimately cause total loss of hearing and since a state deafer than deaf is inconceivable and meaningless it is evident that these components cannot remain additive near the limit.

Realism may be better served by Fig. 10.26, where the upper margin represents total loss of hearing attainable by various routes. Cataclysmic noise dose and hyperlongevity represent the extremes. The non-noise-exposed, barring other hazards, will follow a course such as OABC. The noise-exposed will suffer an additional loss, represented by the line ODEC, which corresponds to Fig. 10.17, and the total hearing loss must follow some such course as ODFC, where the ordinate of curve DF is at first equal to the sum of the ordinates of curves DE and DAB, but later is less than their sum since point C cannot be surpassed.

A possible algebraic representation of this modified summation is as follows. Let f, g represent OAB, ODE respectively. Then ODF is given by k where $k = f \dotplus g = f + g - fg/H_\infty$, H_∞ being the "ultimate" hearing loss; the symbol $\dotplus$ representing asymptote-limited summation. This algebra extends indefinitely to additional items. For example, one could imagine a sudden event (gunfire, pathology, etc.) occurring at age G (Fig. 10.26), of such a type that in a young person of normal hearing it would cause hearing loss h along a course OGJK. In the non-noise-exposed person, we should expect the course OAHLMC, the segment LM being determined by

$$l = f \dotplus h = f + h - fh/H_\infty$$

For the noise-exposed person, however, the extra event G modifies his original course (curve k) to ODNPQC (curve M) where

$$m = k \dotplus h = (f \dotplus g) \dotplus h = f \cdot (g \dotplus h)$$

$$= f + g + h - (fg/H_\infty) + (fgh/H^2_\infty)$$

(the algebra being commutative).

The effect of the modified addition ($\dotplus$) is quite small until one or other of the terms being added approaches the limit. Ordinary addition would not be violated within experimental error over the whole of the lower half of the diagram. The modification deals satisfactorily, however, with the philosophical difficulty associated with the limit and may be capable of direct verification from a study of presbycusis and/or noise-induced deafness amongst persons suffering severe additional losses from other causes. Our data, having been purged of such cases, do not permit us to take this question further.

There remains a difficulty about the value H_∞. This might arbitrarily be taken as the highest reading on the audiometer but such a choice offers no intellectual attraction. Audiometry is so practised that H is measured by how much a sound must be *raised* to remain just audible, and there is no clear limit save that at which instant physical damage would be caused to the remanent auditory mechanism of the subject. It could be measured by how much *less* activity occurs in the deaf ear compared with the normal, for the same stimulation. Except for simple conductive deafness, however, this would imply a neurological measurement and a new problem would arise. How could this scale of measurement be related to hearing loss, measured in decibels, the only terms in which the curves have the particular form we have presented? A similar problem arises if the right-hand scale of Fig. 10.26 is considered. Perhaps it is more logical to measure hearing loss from a normal 100% down to 0% at "no residual hearing", rather than upwards in an arbitrary scale of decibels. Moreover, if the curves f, g, h etc. were expressed on the scale of residual hearing it is probable that the combined effects of two or more causes could be put in the simple multiplicative form fg, fgh etc. There seems, however, to be no way whatever of devising a natural scale of residual hearing having the ratio and interval properties required of a valid measuring scale.

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Appendix 11

Experimental basis for the concept of noise immission level

by D. W. Robinson and Judith P. Cook

Introduction

That the effect on hearing induced by long-term exposure to noise must depend both on the noise level and the duration of exposure is self-evident if one leaves aside the extreme case of instant trauma: whether it is possible to define a compact function of these two variables representing the total exposure is not so obvious.

Certainly a determinate relationship must exist between noise level and duration. For if one considers a particular audiometric frequency and a specified noise level, there must be a unique duration which, in the combined effect, produces any chosen value of the hearing level. Moreover, the nature of the relationship is obviously an inverse one, though not necessarily simple. To be "compact", as we mean it here, the relationship would have to be both simple in a mathematical sense and independent of the audiometric frequency.

We do not, of course, mean to imply that such a relationship must be assumed to exist and force-fitted to the data. On the other hand if the assumption is compatible with the experimental evidence it would greatly simplify the assessment of noise environments in relation to hearing preservation and damage risk.

We should also add that in writing of a unique relationship we do not imply that all persons respond equally to noise: this is very far from the case and is among the chief reasons why quantitative study of the essential functional relationships in hearing are difficult, tedious and unavoidably statistical in character.

The conclusions presented in this Appendix are based on an analysis of the results of the 581 cases accumulated up to the beginning of 1967, and seem to provide a rather clear and positive answer to the question posed above.

Outline of conclusion

Our conclusion, based on a test of statistical significance, is simply stated: the direct product of the duration and the sound intensity is a

characteristic measure of noise exposure. Lest this result be thought unremarkable because it happens to be the simplest physical relationship, the quantity in question being directly proportional to the total energy received, we would anticipate the argument on which it is based to note that it emerges from an indirect though rather sensitive numerical process, and also that a variety of different empirical relationships have been postulated in the literature. Confidence in the conclusion is reinforced by the rather wide range of exposure histories in the present study: about 80 to 115 dB(A) embracing a wide variety of frequency spectra, and from 1 month to 50 years of constant daily exposure in known noise.

There are two qualifications to the conclusion as stated above. The first concerns the measure of sound intensity. As we have shown in Appendix 10, noises with different spectra are realistically compared with regard to persistent threshold shift when the A-weighting is used. Thus our conclusion, more precisely stated, is that the characteristic quantity is A-weighted noise immission, which is proportional to the integrated sound energy through a factor depending on the spectral distribution of the noise. The second qualification concerns the range of durations over which the A-weighted energy principle is valid. This may justifiably be taken as coterminous with the range of exposure times encountered in our subjects viz. 1 to 600 months, but cannot properly be extrapolated beyond either limit. However it would lead to a dramatic simplification of hearing conservation rules, as well as of hearing loss risk prediction and the associated acoustical instrumentation, if the energy principle operated more generally in the time domain and it may well turn out that this is so. At present, however, we have located no suitable subjects having a regular daily exposure consisting of cyclic on- and off-periods or of single bursts on which to test this hypothesis. The equal-energy principle, if applied to exposure durations on the scale of minutes or hours, would conflict fundamentally with the current fashion which relies on the proposition that noises producing equal temporary threshold shift (TTS) measured at a given lapse of time, usually 2 minutes, after the last significant noise exposure period on any day, represent equal hazard i.e. produce equal persistent threshold shift. However, in spite of its widespread following the TTS equinocivity principle is itself an untested hypothesis (1) probably for the same reason: namely the difficulty of procuring experimental evidence.

Experimental data

The audiometric measurements available for this study consisted of left and right ear hearing levels at 0·5, 1, 2, 3, 4 and 6 kHz for 581 subjects. As a first step, the mean value for left and right ear was taken and a correction for presbycusis to a notional age of 20 years made according to frequency and the chronological age of the subject. For this purpose the smoothed version of Hinchcliffe's results (2) referred to in Appendix 10 was used. The subjects were next classified in 20 groups according to duration of exposure (5 bands) and noise level (4 bands). The dividing lines between bands were based on the consideration of roughly equalising the number of subjects in each cell. The mean noise level L_A and the geometric mean exposure duration T were then calculated for each group. The use of the geometric mean for the exposure measure was suggested by the approximately linear form of the regression curves that result from relating the logarithm of duration to the mean hearing level for all subjects in a given noise band, as illustrated in Fig. 10.7. The arithmetic mean of the age-corrected hearing levels at a given frequency was taken to represent the hearing level of the group. This hearing level was next expressed relative to the corresponding value (i.e. for the appropriate frequency) for a group of 97 non-noise-exposed subjects. These controls, save for the noise, were selected according to the same criteria as the noise-exposed subjects, and tested under identical conditions. The resultant differences, H, may thus be termed *presumed noise-induced threshold shift.*

In order to determine a relationship between L_A and T for constant H, it is desirable that the error in the experimental determination of H should exert the least influence. For this reason, after inspection of the data, it was decided to confine the analysis to 3, 4 and 6 kHz at which frequencies the main effects L_A and T are much larger whilst the dispersion of H within groups is increased to a lesser extent.

Table 11.1 shows the data in this reduced form.

Determination of relationship

If the data in Table 11.1 are plotted in the form of H against L_A with T as parameter, a first approximation is a set of straight lines. If they are plotted in the form of H against log T with L as parameter a first approximation is again a set of straight lines. This suggests a composite relation of the form:

$$H = A\,(L_A + k \log T/T_O) = A.E(k)$$

where A is a constant, and T_O is an arbitrary reference duration.

By assigning different trial values to k, the term in the brackets was computed and the data replotted as a set of curves in the form H against E(k). The result for various k was in each case a mildly accelerating function (rather than a straight line) which, having regard to the scatter of the 20 data points, could be adequately fitted by curves of the second degree in E, thus:

$$H = a + bE + cE^2$$

in which a, b, c and E depended on the chosen value of k.

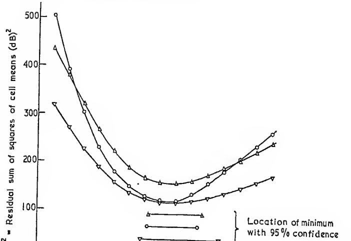
TABLE 11.1
Noise, exposure duration and hearing level data for 20 groups of subjects

Exposure band (months)	Noise level band*	Mean noise-induced threshold shift H (decibels)		
		3	4	6 kHz
1–12	1	1·6	2·8	1·2
	2	4·5	4·6	4·3
	3	6·7	8·1	5·9
	4	9·0	14·5	10·8
13–24	1	0·2	−0·4	1·5
	2	2·0	3·5	5·9
	3	3·6	5·2	5·3
	4	5·8	11·1	5·7
25–48	1	2·7	3·7	1·7
	2	2·4	3·2	4·6
	3	11·2	14·7	12·4
	4	13·0	17·3	11·7
49–168	1	2·8	6·7	1·9
	2	3·7	8·0	5·4
	3	9·2	12·5	9·8
	4	22·1	28·6	17·7
169–600	1	2·7	6·1	3·5
	2	4·5	12·0	7·5
	3	22·1	23·3	18·9
	4	27·4	33·3	25·9

*1 : <90 2 : 90–94 3 : 95–99 4 : ⩾100 dB(A)

The residual sum of squares S^2 of the 20 data points about the quadratic curve is $\sum_{i,j} (H-H_{ij})^2$ where the suffixes i and j represent exposure duration and noise level bands respectively. For each k, the value of S^2 can be calculated; for one such value S^2 has a minimum value, and that value $k = k_0$ determines the most probable form of E and hence the relationship between L_A and T.

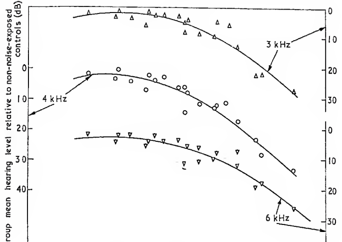
This procedure was carried through independently for the data at 3, 4 and 6 kHz with the results shown in Fig. 11.1. It can be shown that S^2 is a rational function of the sixteenth degree in k. The sharpness of the minimum and hence the significance of the minimum value k_0 obviously depend on the random error in relation to the main effect, and as expected the minimum is rather better defined for the 4 kHz results than the other frequencies.



11.1 Dependence of the residual variance on the exponent of duration. Number of cells, 20 (4 noise levels × 5 duration bands); average data per cell 58 (29 subjects × 2 ears). Symbols: 3 kHz, △; 4 kHz, ○; 6 kHz, ▽.

The value of k_O is seen in each case to lie in the neighbourhood of 9; indeed the similarity is remarkable in view of the independence of the calculations and their rather sensitive dependence on the input data. We carried through analogous calculations in terms of the 581 individual H, L_A and T values instead of using grouped data as a check on the result. The arithmetic involved was heavy and the result disappointing owing to the large scatter in the original data, which produced a very flat minimum of the S^2 curve.

The way the grouped data look when fitted by the near-optimum E-function with $k_O = 10$ is shown in Fig. 11.2. The abscissa E is the A-weighted noise immission level in decibels relative to a reference level of 0 dB(A) at the rate of 8 hours daily for 1 working month. The reason for the lack of success with the calculation based on individual data is not difficult to discern when one looks at the



11.2 Second-order regression curves relating group hearing level to noise immission level. Number of subjects (20 groups) 581. Noise immission level $E_{A2} = L_{A2} + 10 \log (T/1 \text{ month})$.

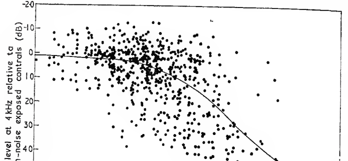
scatter: Fig. 11.3 contains the same data at 4 kHz as Fig. 11.2 in ungrouped form.

A significance test for k_O was provided for us by Mr. J. G. Hayes of the Division of Numerical and Applied Mathematics, National Physical Laboratory. If the quadratic approximation to the S^2 versus k curve in the neighbourhood of the minimum is written in the form $S^2 = S_o^2 + (k - k_O)^2/K$, the standard error of k_O is

$$S_o \left\{K/(n-4)\right\}^{\frac{1}{2}}$$

where n is the number of data points fitted, namely 20.

Inasmuch as the results for the three audiometric frequencies are computationally independent of each other, and bearing in mind that there is some correlation between the hearing levels of an ear at different frequencies, we estimate that the value of k_O is 9 ± 2 with 98% confidence; i.e. it does not depart significantly from the value $k_O = 10$. In view of this, and because an energetic principle seems fundamentally appropriate to account for an irreversible biological



11.3 Individual age-corrected hearing levels, at 4 kHz, relative to controls unexposed to noise, plotted against noise immission level. Number of subjects 581. Noise immission level $E_{A2} = L_{A2} + 10 \log (T/1 \text{ month})$.

change, we are led to believe that frequency-weighted energy may indeed be the essential physical quantity determining noise-induced loss of hearing.

Quadratic functions have been assumed in this analysis since they approximate sufficiently to the data, having regard to the dispersion. As discussed in Appendix 10, a relationship of the form:

$$H = a \left\{ 1 + \tanh \frac{E - E_O}{\mu} \right\}$$

is logically preferable in that its limiting behaviour for zero and large noise immissions is more plausible. Programming for the minimisation of S^2 using such forms was considered unnecessarily involved for present purposes. A curve of this type approximating the median hearing loss is shown on Fig. 11.3.

Implications of the concept of immission

If we are correct in ascribing a fundamental significance to the quantity that we have termed noise immission level, i.e. a noise level in decibels plus 10 times the logarithm of a duration, we may also have succeeded in raising the possibility of explaining certain aspects of the mechanism of hearing damage out of the empirical on to a physical plane. It is beyond our present competence to postulate a physiological model that would accord a one-to-one correspondence between an element of the irreversible hearing-loss process and a finite amount of energy required to mediate such a change. It does appear to us, however, that such a model may well exist on general physical reasoning.

If this is so, it would follow that time and intensity could be freely traded on an inverse relationship: otherwise expressed, that immitted energies are cumulative. It is true that our experimental data relate to individuals for whom L_A has been constant (for 8 hours on a 24 hour cycle, 5 or $5\frac{1}{2}$ days a week) throughout the exposure, and what our results imply is that any combinations of L_A and T such that

$$T_1 10^{L_1/10} = T_2 10^{L_2/10} = T_3 10^{L_3/10} = \ldots\ldots$$

produce equal effects. It is a small step to the conclusion that a composite noise exposure consisting of periods T_i at levels L_i will also have the same effect provided that $\sum_i T_i 10^{L_i/10}$ has the same

value as above: indeed it is difficult to visualise any mechanism whereby this extension would be invalidated, provided that the component elements of the summation lay within the range of validity of the fundamental proposition. By way of numerical example, the following sets of exposures (i) (ii) and (iii) will almost certainly produce the same result in the average person (exclusive of considerations of presbycusis):

(i) daily exposure to 100 dB(A) for 2 years

(ii) daily exposure to 90 dB(A) for 20 years

(iii) daily exposure to 100 dB(A) for 1 year followed by daily exposure to 90 dB(A) for 10 years

It would be a fortunate state of affairs if, to the above examples, one could add a fourth and a fifth:

(iv) as (i) except that the daily exposure consists of 1 hour at $100 + 10 \log 8 = 109$ dB(A)

(v) as (iv) except that the 1 hour is divided into n periods of 1/n hours each, or such that the total noise immission is equal if it occurs in irregular bursts.

Almost total lack of experimental data for persons with exposures type (iv) and (v) going back over a sufficiently long period of time unfortunately precludes a definite conclusion that (iv) and (v) *are* equivalent to (i) (ii) or (iii). In case (v) it is possible to visualise mechanisms that would render it non-equivalent to the other cases.

There is one class of noise exposure at the extreme end of the on-time duration range viz. milliseconds, for which a considerable amount of audiometric data is published, namely exposure to gunfire. If it could be shown, even to an order of magnitude, that such data fit in with those from our 581 subjects with long-term continuous noise it would be a highly significant extension of the energy principle, bridging over the experimental gap for on-time durations of the order minutes per day. Our hopes of success in this enterprise were slender, because, amongst other complications, the actual sound pressures involved are quite outside the range of industrial noises and there is no certainty that the auditory mechanism remains linear up to this

region. We have examined the literature of gunfire case histories; unfortunately most of these reports are unaccompanied by oscillographic or equivalent recordings of the acoustic waveforms, and there is none that we have found in which the physical stimuli are described in a way to permit us to estimate the noise immission level within an acceptable tolerance. This line of enquiry does, however, appear to us to be promising and to merit further study.

References

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Appendix 12

Serial audiometry and the prospective study

by D. W. Robinson and Lynda A. Burdon

Introduction

The larger part of the serial investigation employed subjects from among the 759 featuring in the retrospective survey. Those with the longer histories of noise exposure were excluded; as many subjects as possible with no initial exposure were brought in. Conditions could not be established for a true prospective study covering a substantial period of time except in 9 miscellaneous cases. This group was considered to be too small for separate study and it is included in the serial investigation. The ideal condition of zero initial exposure was obtained with a homogeneous group of 22 school leavers and the results for this group are considered separately.

Table 12.1 summarises the gross numbers. The largest number of audiometric tests administered to any subject, apart from any TTS or repeat measurements, was 4. Tests were separated by 11 months on the average.

TABLE 12.1
Summary of number of audiograms taken

Number of times tested	Number of subjects		
	Noise-exposed	Controls	Total
1	790	97	887
2	515	39	554
3	214	17	231
4	34	0	34

Classification of subjects

Preliminary analysis of the data accumulated up to mid-1966 showed that there was an appreciable fraction of persons whose audiometric performance was unstable or marred by excessive error, resulting in implausibly large differences between the left and right

ear threshold shifts. These cases appeared to be of scattered occurrence not related to any observed factor. The effect of including such results is only to dilute the main effect by increasing the already considerable random scatter. It was therefore decided for some purposes to eliminate those exceeding a certain level of inconsistency.*

In addition, a number of results exhibited very large shifts, positive or negative, without necessarily exceeding the interaural unbalance criterion. These were critically examined by scrutiny of the original and follow-up questionnaires and the audiograms. Some large negative shifts were associated with dramatic improvement in performance at the audiometry, showing that the first-test results could not have been correct. Three or more serial audiograms naturally facilitate the detection of these cases. Extreme caution was applied before rejecting apparently excessive positive shifts. A total of 24 subjects was eliminated as a result of this examination. In a few cases with 3 or 4 tests, the first result was discarded, the second being reckoned as the first and the initial exposure time adjusted accordingly.

In composing the groups for final analysis a modification was made to the unbalance criterion, to a form more suitable for the computer.† The total number with 2 or more tests at this stage was 530 of whom 61 comprised the non-exposed controls and school-leavers, and a further 61 the cases eliminated by the revised unbalance criterion. To avoid tedious repetition in the following paragraphs we shall denote various groups of subjects by code letters as set out in Table 12.2.

Preliminary analysis

An initial examination of the results of the serial audiometry was carried out at the time when 339 double tests and 147 triple tests were

* The criterion adopted was that the signless average of the difference between the left and right ear threshold shifts at 3, 4 and 6 kHz should not exceed 10 dB.

† The mean threshold shift for each ear at 1 and 2 kHz was subtracted from the mean threshold shift at 3, 4 and 6 kHz. If the resulting values differed by 10 dB or more for the two ears the subject was eliminated. There were 61 such cases out of a total of 530. Of these, the average of the quantities calculated for the left and right ear was negative in 33 cases and positive in 28. For this reason it did not make much difference in the subsequent analysis whether the 61 results were retained or rejected.

TABLE 12.2

Group classification of subjects

Group Code Letter	Number in Group	Number with 2 tests	3 tests	4 tests	Note
A	469	469	226	34	a
B	408	408	203	31	b
C	237	237			c
D	25	25	12	0	d
E	22	22	0	0	e
F	39	39	17	0	f

Notes

a Consists of 484 in retrospective survey, plus 9 witb zero initial exposure, less 24 eliminated after review of audiograms and questionnaires.
b Group A less 61 exceeding interaural unbalance criterion $| Y_L - Y_R | \geqslant 10$.
c Group B less 171 with initial exposure exceeding 2 years. Includes 7 witb no previous exposure, 11 with 1 month and 8 with 2 months.
d Part of Group C; those witb the highest noise levels.
e School-leavers; first tests before exposure, second tests 2 months later.
f Controls not exposed to noise.

to hand. These were reduced to 144 and 58 respectively by the rather severe elimination criteria applied in 1966. They were sorted into 5 noise level bands and the threshold shifts normalised, in a first trial, by dividing by the intertest time interval. This gave a nominal measure of deterioration rate in decibels per annum. The average rates for the 5 groups showed no clear trend with increasing noise level, suggesting that a more sophisticated treatment was necessary.

The refinement was introduced of calculating an impairment rate index

$$s = \tfrac{1}{2}(s_L + s_R) = \tfrac{1}{2}(\Delta_L + \Delta_R)/\log\left((1 + \tfrac{T}{T_0}\right)$$

Δ_L and Δ_R being the age-corrected* left and right ear threshold shifts averaged over 3, 4 and 6 kHz. T_1 is the initial exposure time and ΔT the time interval between tests. In comparing subjects with different T_1 and ΔT values, this normalising formula takes more realistic account of the diminution of the impairment rate with time. Had the mathematical form of the impairment curves been evolved from the retrospective survey these would have been used to provide a stil better normalisation, but these curves were not available in 1966. Th

* The age correction is small, being only the difference in presbycusis due to the time lapse between tests.

index s was found to increase more or less smoothly with noise level but the number of subjects was rather small to expect clear-cut results. Only the highest and next-to-highest noise level bands with 10 and 15 subjects respectively showed any marked signs of actual hearing deterioration.

At this time the list was deficient in persons, particularly young persons, with little or no previous history of noise exposure. Field work was intensified throughout the latter half of 1966, and the whole of the following year, when it was brought to a close. By this time the list had improved in numbers and composition to the state shown in Table 12.2. In addition, the retrospective survey and its analysis were by then complete, providing a more refined framework for examining the results of the serial audiometry.

Final analysis

We begin by examining the dispersion, dominated by random error, against which to view the experimental evidence for systematic noise-induced threshold shifts. No amount of statistical sophistication can conceal the fact that the vast majority of the observed threshold shifts are more illusory than real due to the limitations of accuracy inherent in conventional audiometry. But in later paragraphs we shall show how in spite of this it is possible to draw certain conclusions.

Threshold shift variance

We are concerned here with the variance of the age-corrected threshold shift, the latter being denoted by the general symbol $\Delta = H_O^n - H_O^1$. H_O is the age-corrected hearing level of a given ear at a given audiometric frequency, and the superscripts refer to the ordinal numbers of the tests. The quantity Δ may be averaged over left and right ear, or over more than one frequency, or both. The notation used is as follows:

Δ_{L3} means threshold shift, left ear, 3 kHz. Similarly for other frequencies.

$\Delta_{L\overline{346}}$ means threshold shift, lcft ear, averaged over 3, 4 and 6 kHz. Similarly for other combinations.

Δ_{LR} denotes the average threshold shift for left and right ear.

Variance of Δ is denoted by σ^2 with the corresponding subscripts.

Y denotes tbe particular combination ($\Delta_{LR\overline{346}} - \Delta_{LR\overline{12}}$). This is a measure of the extent to which high frequency thresbold shift is gaining on mid-frequency threshold shift, that is, tbe progression of the 4 kHz dip.

Variance of Y is denoted by σ_Y^2.

Table 12.3 summarises the variance calculated for various subject groups, and arranged in ascending order. If measurements of Δ were free from error we sbould be able to identify tbe variance of Δ about its mean witb differences of threshold shift susceptibility between persons. We sbould also expect no individual value of Δ to be less than zero. This, clearly, is far from the case with the actual measurements. If it bad been possible to replicate each determination of hearing level the observed total variance of Δ could have been analysed into residual error and difference between subjects. This was not, unfortunately, a logistic possibility. The best we can do is to take σ^2 as it comes, except in case of Group B wbere the refinement of calculating regression variance was made. The manner of obtaining this is described later but it is sufficient to note here that the effect of allowing for the systematic differences of threshold shift expected for different noise levels and exposure histories is only to reduce tbe gross variance in Group B from 17.8 to 17·4 (dB²). Moreover, there are clear indications from the excellent fit of the serial results to the curves derived from tbe retrospective survey, tbat the latter realistically portray the events that occur. Tbe order of magnitude, if not precise values, for the intersubject component of the variance of Δ can therefore be estimated and it turns out to be very small compared to tbe gross variance (roughly 0·6 out of 17·8 for Group B). We conclude that the variance of Δ is almost wbolly accounted for by random

TABLE 12.3

Summary of threshold shift variance

Group	Variance (dB²)		
	$\sigma^2_{LR\overline{12}}$	$\sigma^2_{LR\overline{346}}$	σ^2_Y
F	7·6	9·5	8·4
E	9·6	10·5	9·8
B	—	20·5	17·4
D	—	22·1	—

errors. The occurrence of almost equal numbers of positive and negative values of Δ may be felt to make this conclusion sufficiently obvious, even in the absence of theoretical arguments.

It is apparent from Table 12.3 that there is a progressive decrease in the reliability of threshold measurements associated with a longer history of noise exposure. The same thing is remarked in connection with an indirect analysis of variance of the retrospective data (see Appendix 10). It remains unexplained but may be psycho-sociological in origin; certainly such differences could well have existed between Groups D, E and F and between these and subject groups in laboratory studies where variances even lower than those in our control group (office workers attached to the factories) are found routinely. Given pure-tone audiometry as it is today it appears that these measures of unreliability are characteristic and unavoidable.

A more detailed breakdown of the variance is shown for Groups D, E and F in Tables 12.4, 12.5 and 12.6. The main block of each Table gives the variance for each ear and each frequency separately, then for the left-right average at each frequency and for the 3-frequency average with each ear, and finally the grand average. Also shown are the estimates of the variance for these partial and grand averages that would be made from the individual observations on the assumption that there was no correlation between any of the 6 quantities concerned. Comparison with the actual values shows that such estimates would invariably be optimistic, or otherwise expressed that there is some correlation. The variance of the average of highly correlated quantities is no smaller than that of any one of the quantities, whereas if they are uncorrelated it is inversely proportional to the number of items in the average. The correlation coefficients can be inferred from the data and are shown in the Tables.* The values are generally small, though some are highly significant. The conclusion to be drawn from these calculations is that averaging of the threshold shifts over ears and frequencies is almost wholly efficient in reducing the random error. As the systematic component of the

* The mathematical relationships between the tabulated quantities are as follows:

$$\sigma^2_{\overline{LR}}/\left\{\tfrac{1}{4}(\sigma^2_L + \sigma^2_R)\right\} = 1 + r_{LR}$$

and

$$\sigma^2_{\overline{346}}/\left\{\tfrac{1}{9}(\sigma^2_3 + \sigma^2_4 + \sigma^2_6)\right\} = 1 + \tfrac{2}{3}(r_{34} + r_{46} + r_{63})$$

where r_{LR} denotes the correlation coefficient between Δ_L and Δ_R, etc.

TABLE 12.4

Breakdown of threshold shift variance: Group F

Frequency (kHz)	Variance (dB²)				Correlation coefficient r_{LR}
	σ_L^2	σ_R^2	σ_{LR}^2	$\frac{1}{4}(\sigma_L^2+\sigma_R^2)$	
3	19·0	22·3	12·9	10·3	0·25
4	29·6	41·8	22·9	17·8	0·29
6	47·8	76·4	40·2	31·1	0·29
Mean at 3, 4 & 6 ($\sigma_{\overline{346}}^2$)	15·4	20·6	9·5	9·0	0·06
$\frac{1}{9}(\sigma_3^2+\sigma_4^2+\sigma_6^2)$	10·7	15·6	8·4		
Mean correlation coefficient (r_{34}, r_{46}, r_{63})	0·22	0·16	0·07		

noise-induced threshold shift is also not much different at 3, 4 and 6 kHz there is little doubt that the measure $\Delta_{LR\overline{346}}$ is an efficient one for serial audiometric studies.

The correlation coefficients shown in Tables 12.4, 12.5 and 12.6 refer to threshold shifts, not to absolute hearing levels, so it is not surprising that they are smaller than has been reported in the other case (1). Indeed, it is perhaps surprising in the face of the random error that any appreciable correlation exists at all. We believe that it

TABLE 12·5

Breakdown of threshold shift variance: Group E

Frequency (kHz)	Variance (dB²)				Correlation coefficient r_{LR}
	σ_L^2	σ_R^2	σ_{LR}^2	$\frac{1}{4}(\sigma_L^2+\sigma_R^2)$	
3	36·6	19·8	17·0	14·1	0·21
4	24·5	29·1	18·9	13·4	0·41
6	67·6	57·0	51·2	31·2	0·64
Mean at 3, 4 & 6 ($\sigma_{\overline{346}}^2$)	18·2	14·5	10·5	8·2	0·28
$\frac{1}{9}(\sigma_3^2+\sigma_4^2+\sigma_6^2)$	14·3	11·8	9·7		
Mean correlation coefficient (r_{34}, r_{46}, r_{63})	0·14	0·12	0·04		

may be due to an extraneous factor, namely an observed tendency for successive audiograms to be displaced bodily upwards or downwards, quite apart from any irreversible shifts. There could be at least three *prima facie* explanations for this:

(a) secular calibration drift.

(b) earphone fit.

(c) subjects' "set".

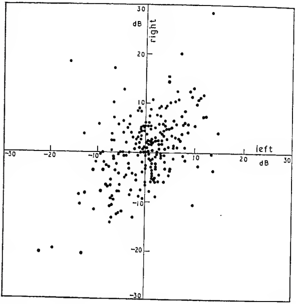
TABLE 12.6
Breakdown of threshold shift variance: Group D

Frequency (kHz)	Variance (dB²)				Correlation coefficient r_{LR}
	σ^2_L	σ^2_R	σ^2_{LR}	$\frac{1}{4}(\sigma^2_L + \sigma^2_R)$	
3	32·1	44·8	18·3	19·2	0·05
4	39·9	52·9	30·3	23·2	0·31
6	134·3	141·3	105·3	68·9	0·53
Mean at 3, 4 & 6 ($\sigma^2_{\overline{346}}$)	28·4	33·3	22·1	15·4	0·44
$\frac{1}{9}(\sigma^2_3 + \sigma^2_4 + \sigma^2_6)$	22·9	26·6	17·1		
Mean correlation coefficient (r_{34}, r_{46}, r_{63})	0·12	0·13	0·15		

We are confident from examination of the daily calibration log sheets maintained throughout the 5 years of the investigation that cause (a) can be discounted. Cause (b) would show up as a false correlation between frequencies if faulty fit of the earphone resulted in a general upward or downward error in the sound pressure levels produced; this is not very likely at high frequencies. It is even less likely to happen in the same direction on both ears simultaneously, and so does not seem to be the most likely explanation. This leaves cause (c) which is almost certainly at work. The total lack of control of subjects' set, that is the attitude he takes up in the "risk-taking" decision whether or not to press or release the audiometer reversing button, is quite likely to account for a large part of the variance which at present we describe as "random". To eradicate this source of uncertainty would be very useful and it is clearly a rather difficult exercise in applied psychology.

This tendency to drift was more marked in some subjects than in others, the effect on the average not being very great. It suggested to us, however, that the serial data might reveal a clearer picture if we could somehow eliminate it. Fortunately this can be done, taking advantage of the fact that the noise-induced threshold shift is frequency-dependent. The mean hearing level at 1 and 2 kHz was used to peg the level of the initial and subsequent audiograms, and the mean relative threshold shift at 3, 4 and 6 kHz used as the index of change. In our notation this defines the quantity Y. It turned out that this device was more effective than consideration of the straight-forward high-frequency threshold shifts, as is discussed below.

An effective way of displaying measured threshold shifts to show the scatter is to plot the results for left ear against those for right, as

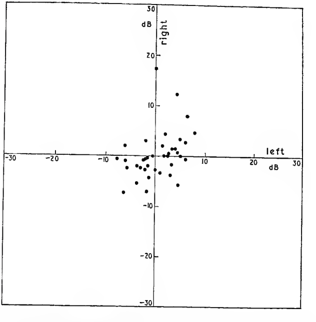


12.1 Threshold shifts (average of 3, 4 and 6 kHz) in left and right ear of 237 noise-exposed subjects (group C). Exposure duration $T_1 \leqslant 24$ months.

in Figs. 12.1 and 12.2 which relate to Groups C and F. Ideally the data in Fig. 12.1 would lie along the principal diagonal in the first quadrant only. Those in Fig. 12.2 should collapse to a small cluster close to the origin.

Variation of threshold shift with noise level

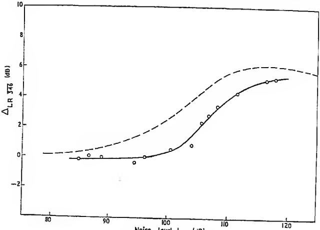
To illustrate this relationship the subjects of Group C were arranged in ascending order of noise level L_{A2} and regrouped in 13 overlapping bands containing on the average 38 persons. For each band, averages were calculated for the noise level L_{A2}, the initial exposure time T_1, the time lapse between tests ΔT, and the threshold shift $\Delta_{LR\overline{346}}$. The mean threshold shift was adjusted according to the



12.2 Threshold shifts (average of 3, 4 and 6 kHz) in left and right ear of 39 non-exposed controls (group F).

mean ratio $(T_1 + \Delta T)/T_1$ for the band relative to the grand average of this ratio for Group C, using the logarithmic approximation mentioned earlier. The resulting values are plotted on Fig. 12.3 against the average noise level for the band. The dotted line is the expected result calculated from the formula in Appendix 10, using the grand average values of T_1 (12·6 months) and ΔT (16·2 months). There is some difference between the two results but a striking similarity of form. The calculated curve passes through a maximum because the deterioration in the first 12 months at high noise levels begins to flatten off so that the increment in the next 16 is less than it would be at lower noise levels (the total is of course greater). The serial data do not extend high enough up the noise scale to verify this directly, although they appear to be approaching the maximum.

The discrepancy in magnitude may be due in part to a learning effect, tending to reduce the measured threshold shifts. But there is little evidence for this among the low-noise members of Group B whose threshold shifts in fact average zero. Another contributory



12.3 Variation of threshold shift (average of 3, 4 and 6 kHz) with noise level, for 237 subjects (group C). T_1 <24 months; $\overline{T_1}$ = 12·6 months; $\overline{\Delta T}$ = 16·2 months. Symbols: experimental results, O; calculated results (see appendix 10), interrupted line.

cause of overprediction might be the assumption that the only significant noise exposure is that attributed to the subjects' occupations. Miscellaneous noise immission prior to entry into the known noise would diminish a later threshold shift, the more so the smaller the value of T_1 assigned to a subject. Arbitrarily taking the pre-occupational exposure to be the equivalent of 3 months occupational exposure, the dotted line was recalculated; but the displacement is too small to offer a full explanation.

Read in conjunction with Fig. 12.1, the experimental results on Fig. 12.3 well illustrate the difficulties in the way of short time-base serial audiometry. For the important industrial range 90 to 100 dB(A) the median shift is seen to be a couple of decibels. The values would be roughly doubled if instead of having to settle for T_1 equal to 12·6 we could have secured pre-exposure audiograms, other things remaining unchanged. To double it yet again, the time lapse between tests would have to be increased from 16 months to about 5 years, clearly an impractical undertaking.

Personal variations

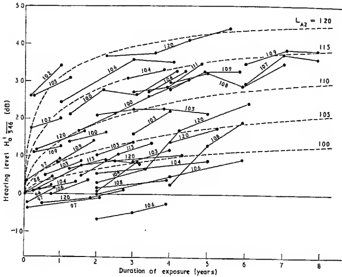
The small threshold shifts expected for the median subject will be considerably exceeded by susceptible persons. A general idea of the results obtained may be gained from Fig. 12.4. The expectation for the median is shown by a series of dotted lines for noise levels L_{A2} of 100, 105 . . . 120. Superimposed are 42 specimen results at appropriate positions along the time scale, the zero of which denotes the subject's entry into noisy occupation. Each plot is numbered with the subject's noise level. In order not to overload the diagram a selection of the more regular serial results has been made. A glance at the Figure is enough to show that the general trend is overlaid with very large personal variations.

Learning effect

A number of studies have been directed by authors to this question for several modes of pure-tone audiometry and varying periods of time between tests, and progressive lowering of the hearing level is usually reported. In an unpublished study Delany (2) found that the improvement within a day spent doing 4 audiograms had partly disappeared the next day, so that over a whole week the results

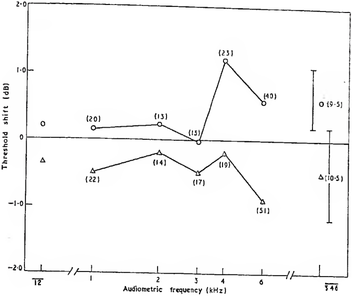
resembled a saw-tooth superimposed on a small persistent slope. Our tests were separated by much longer periods and we find that the learning effect is negligible except in a proportion of cases where, as already mentioned, the progressive reduction in the measured hearing level is accompanied by increasing aptitude at the test as judged by the excursions on the self-recorded audiograms. Clear cases of this type were eliminated; no doubt less exacerbated cases remain within our data for there is no sure way of diagnosing them.

We have examined the results in Groups E and F which are shown on Fig. 12.5. The ordinate is the mean threshold shift; the variance in dB^2 is indicated by the numbers in brackets. The standard error of the 3, 4, 6 kHz average is 0.69 and 0·49 dB for the two groups respectively so that no point on the diagram is significantly different from



12.4 Results of serial audiometry (42 examples). The interrupted curves are calculated from the results of the retrospective study. The numbers on the examples are the noise levels L_{A2} to which the individuals were exposed.

zero. The controls show a marginal hearing loss whilst Group C paradoxically show a marginal improvement. The latter group was retested after the comparatively short interval of 2 months, so it is just possible that the difference is due to reinforcement of learning in the same way as Delany found. Group C can be broken down into C_1 (7 subjects with L_{A2} equal to 95) and C_2 (15 subjects with mean L_{A2} equal to 87). Table 12.7 gives these results together with the small but not negligible expectation calculated from Appendix 10. The learning effect may be inferred by subtraction. The threshold shift in group C_1 is greater than that in Group C_2 in the right direction, but the numbers involved are possibly too few to be conclusive.



12.5 Test-retest variance of threshold shifts for different frequencies and frequency combinations, for the non-exposed control group (F) and for 22 school leavers (E). The test-retest interval for group E was 2 months. The variance, in dB², is shown in brackets for each frequency or frequency combination. The limits for $\overline{346}$ kHz are ±1 standard error. Symbols: controls, O; school leavers, Δ.

TABLE 12.7

Learning effect in Groups E and F

Group	Mean threshold shift (dB)			
	1 and 2 kHz		3, 4 and 6 kHz	
	Observed	Predicted	Observed	Predicted
F	0·19	0·06	0·59	0·12
C_1	0·71	0·30	0·67	0·92
C_2	−0·87	0·11	−1·06	0·32
$C = C_1 + C_2$	−0·37	0·17	−0·51	0·51

Note: The predicted values include a small adjustment for accrued presbycutic loss; otherwise the values for the control group F would be zero.

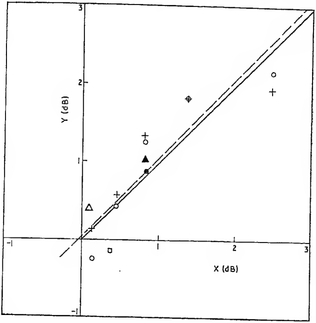
Comparison of serial results with theoretical model

For this purpose it was decided to employ the large group B supplemented by Group E. The age-corrected relative threshold shift $Y = \Delta_{LR\overline{346}} - \Delta_{LR\overline{12}}$ as already defined was found to correlate more closely with the calculated shifts than $\Delta_{LR\overline{346}}$ did, and the comparison is therefore based on the measure Y. The value of Y was computed from the audiometric results of each subject's first and last test. The age adjustment in this case is automatically included by the passage of time. The corresponding quantity, with an adjustment for the change of age, was also calculated by the KDF9 computer from the values of L_{A2}, T_1, ΔT and age of each subject; we denote this calculated value by X. Negative values of X occur in a few cases of advanced hearing deterioration where the loss at 1 and 2 kHz is accelerating whilst the high frequency loss is approaching saturation.

To obtain a broad view of the relation between X and Y the results for Group B were arranged in ascending order of X and regrouped in 5 bands, as shown in Fig. 12.6. Points are also shown for the unexpurgated Group A of 469 subjects. They differ from the 408 of Group B in respect of the 61 whose interaural inconsistency exceeded the 10 dB criterion.

The correspondence between the calculated and observed results is regarded as very good in view of the almost complete independence of the two measures compared, and bearing in mind the scatter of Y.

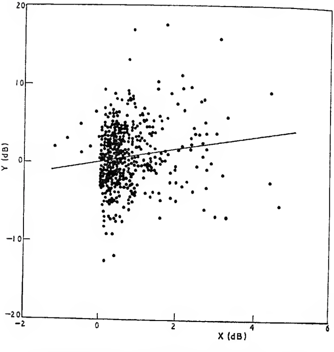
In fact the only thing that X and Y have in common is that the first-test results of the majority of Group B (but not the serial results) formed part of the retrospective survey on which the calculation procedure is founded. The standard errors of the ordinate of the points for Group B range from 0·41 to 0·58 dB; that of Group E is 0·68, and that of the controls (Group F), included for completeness, is 0·47. For Group A the gain in numbers from 408 to 469 is offset by the lesser reliability of the results of the 61 subjects, so that the standard errors are almost identical. Thus no point on the diagram departs from the diagonal by more than one standard error. The dotted line is the calculated regression of Y on X using the grouped



12.6 Correlation between calculated (x axis) and observed (y axis) threshold shift in terms of the quantity Y, a measure of the progression of the 4 kHz dip, for various subject groups. Symbols: Group A, (469 subjects) mean, ▲; bands, +. Group B (408 subjects) mean, ●; bands, ○. Group E, □. Group F, △. Continuous line, Y = X; regression of Y on X (Groups B, E and F), interrupted line.

data with weights proportional to the numbers in each group (B, E and F). It lies very close to the diagonal. The correlation coefficient for the grouped data is 0·98, which is significant at the level $P = 0{\cdot}01$.

The individual data points are naturally much more scattered, as shown in Fig. 12.7. The regression line calculated from the 408 data of Group B is slightly displaced with respect to that in Fig. 12.6. Note that different scale units are used for X and Y in Fig. 12.7 to accommodate the diagram within a reasonable format. The correlation coefficient of the individual data is 0·15, the significance of which



12.7 Individual data from Group B (408 subjects) for the same correlation as in Fig. 12.6. Correlation coefficient = 0·15. The line is the regression of Y on X.

remains better than $P = 0{\cdot}01$, but which appears to be rather small numerically. The degradation compared with the grouped data is very largely accounted for by the random error contained in Y. Theoretically one cannot expect a higher correlation coefficient than

$$r = \left\{\left(1 + \frac{u_X^2}{v_X^2}\right)\left(1 + \frac{u_Y^2}{v_Y^2}\right)\right\}^{-\frac{1}{2}}$$

where u_X^2 and u_Y^2 are the random (i.e. unexplained) components of variance in X and Y respectively, and v_X^2 and v_Y^2 are the explained (i.e. the correlated) components. With this terminology, the total observed variances σ_X^2 and σ_Y^2 are given by the following equations:

$$\sigma_X^2 = u_X^2 + v_X^2; \quad \sigma_Y^2 = u_Y^2 + v_Y^2$$

In the present data $\sigma_Y^2 = 17{\cdot}8$ dB² by direct calculation. Assuming the theoretical prediction of X to be perfect, $u_X^2 = 0$, so that $v_X^2 = \sigma_X^2$ which, calculated from the data, has the value 0·614. The same assumption means that $Y = X$, so that $v_Y^2 = v_X^2$. Inserting these values into the formula we find that the correlation coefficient cannot be expected to exceed 0·186. In reality the prediction X can at best be perfect for the median subject. The formulae in Appendix 10 for the statistical distribution of hearing levels as a function of noise immission level permits an estimate to be made of the intersubject variance that forms part of the unexplained term u_X^2. The computations are tedious due to the non-linear nature of the equations, but a sampling technique was used to obtain an approximate value; the result was 0·50. The attainable correlation coefficient between X and Y is thereby further reduced by the factor $\{1 + (0{\cdot}50/0{\cdot}614)\}^{\frac{1}{2}}$ to 0·138. This is now no higher than the observed value of 0·15, and we may conclude that the theoretical formula predicts the median threshold shift very well indeed.

Satisfactory as this last conclusion is from the standpoint of consistency between different parts of this investigation it in no way assists the interpretation of the meaning of an individual measurement of threshold shift from serial audiometry.

Relation between hearing level and rate of deterioration

During the early stages of noise exposure the accrued threshold shift must be proportional to the rate of deterioration. Later on the relation becomes less direct and eventually disappears. Up to quite a

late stage, however, the correlation should remain high. Thus a susceptible person would be expected to exhibit both an abnormally raised hearing level and a higher than average rate of deterioration in serial audiometry. We have tested this for a group of 35 subjects.* As a measure of relative hearing level we use D_P as defined in Appendix 13, being the amount by which the measured hearing level (averaged over both ears at 3, 4 and 6 kHz) exceeds the median prediction for persons with the same noise immission. As measures of deterioration rate we have used:

(a) The value of Y − X, as defined above
(b) The ratio of Y to X
(c) The rank order of the ratio in (b)
(d) The observed threshold shift $\Delta_{LR\overline{346}}$ minus the predicted value, denoted by D_S

Of these (b) is *prima facie* the most logical since it is self-normalising for different noise and test histories as well as for noise level. The random error in Y however is large (standard deviation ~4) whilst X is only of order 1, so that the ratio is in practice rather unstable particularly for small values of X. These objections are reduced by option (c) but this measure is non-parametric. The measure (a) needs in principle to be normalised before comparing different persons but the computations required to do this were considered excessive for the purpose. This measure is also strongly affected by random error in Y. Measure (d) was not expected to yield the best correlation for reasons already discussed.

If we had had pre-exposure audiograms it would have been possible to define D_P more satisfactorily, by subtracting out the person's base-line hearing level. As it is, our values of D_P unavoidably contain between-subjects variance, the amount of which is in principle the same as exists between persons of normal hearing and the corresponding age distribution. Due to this large and undesired component, high correlations with the various measures of relative threshold shift cannot be realised.

The correlation coefficients, calculated for this group of 35 subjects whose noise levels L_{A2} ranged from 99 to 104, are set out as a matrix in Table 12.8. It includes the measure of relative TTS susceptibility

* These subjects also had TTS measurements and form part of the Group A discussed in Appendix 13. The remaining 18 in this group had TTS measurements but not serial tests.

D_T which is further discussed in Appendix 13. The upper half gives the coefficients, the lower their significance levels for 33 degrees of freedom. Considering the upper row, the correlation is higher between D_P and any of the three measures based on the quantities X and Y than on the direct measure D_S. The last-mentioned is not significant but the correlation between D_P and Y/X is highly significant (P = 0·007). The correlations within the central block of the Table are naturally high but are not of much interest except insofar as the departures from unity in the first row show that the measure D_S is to a certain extent independent of the other three. The correlation between D_T and the deterioration rate measures is rather disappointing, the best being with the rank order of Y/X (P = 0·10). The correlation between D_P and D_T is treated in detail in Appendix 13; the coefficient 0·38 obtained here is to be compared with 0·34 for the larger group of 53 subjects of which our 35 formed part.

It is worth noting that although some of the individual correlation coefficients are not large and some are not significant statistically they are all positive and no really small values occur.

TABLE 12.8
Correlation between various measures of relative hearing impairment

	Correlation coefficient				
	D_S	(Y-X)	Y/X	Rank of Y/X	D_T
D_P	0·26	0·35	0·45	0·31	0·38
D_S		0·72	0·57	0·53	0·21
(Y-X)			0·94	0·97	0·23
Y/X				0·96	0·29
Rank of Y/X					0·28
	Significance level P				
D_P	0·14	0·04	0·007	0·07	0·02
D_S		<0·001	<0·001	0·001	0·24
(Y-X)			<0·001	<0·001	0·19
Y/X				<0·001	0·10
Rank of Y/X					0·10

References

1 Robinson, D. W. *Acustica*, 1961, **11**, 185.
2 Delany, M. E. National Physical Laboratory, 1965 (unpublished).

Appendix 13

The relations between temporary threshold shift and occupational hearing loss

by W. Burns, J. C. Stead and H. W. Penney

Introduction

This Appendix describes the work on the relation between temporary threshold shift (TTS) and occupational hearing loss carried out in this investigation.

The existence of TTS and its possible use as an indication of susceptibility to noise-induced hearing loss have been noted briefly in Chapter 5 of the main report where it was observed that the fairly widespread use of TTS as an indicator of possible long term effects on hearing was largely presumptive. Further, a number of reasons were given why precise information is limited on the relations between TTS and occupational hearing loss, as it affects individuals.

Methods

The principal practical interest in TTS has been its possible use as a prognostic device to classify individuals in terms of susceptibility to noise-induced hearing loss as a result of perhaps many years of occupational noise. Predictive tests have been suggested and discussed (1). In the context of the industrial situation, simplicity in any predictive test based on measurement of TTS is of prime importance. The simplest procedure would consist of a single measurement of TTS derived from an audiogram before the day's work, or resting audiogram, and another at some fixed interval after leaving the working noise environment. In conjunction with the age of the person, the same measurements would also establish the presumed noise-induced hearing loss or age-corrected hearing level relative to controls (H), at the various audiometric frequencies.

Efforts were made to use these simple measures to investigate the relations between TTS and H. For this purpose it was also necessary that the person should have been exposed in the past only to the

particular occupational noise prevailing at the time of the measurements of TTS and H, as well as conforming with the general requirements for acceptability already described in this Report and its Appendices.

Preliminary investigation

Subjects were first grouped on the basis of noise immission level (NIL) (Appendix 11) in narrow ranges of a few dB. Such groups had therefore sustained about the same total energy applied to the ear. It was postulated that those more susceptible to noise-induced hearing loss might show greater TTS. The hypothesis was tested by comparing TTS with H in the persons in these NIL groups. Thus, for example, the TTS at the end of a day's work, averaged over both ears at 3, 4 and 6 kHz, was compared with the value of H similarly derived. Linear regressions for these data were calculated for TTS on H and for H on TTS. No clear picture emerged; large dispersions and low correlation coefficients were found, with regressions in some cases positive, in some negative, but not in any systematic manner.

This procedure was refined by further subdividing the groups on a basis of NIL; grouping by sound level was also tried. These efforts to secure greater homogeneity of the groups produced no significant improvement in the correlation between the TTS and H values.

Attention was next directed to preliminary examination of the possible relation between TTS and the slope of deterioration elicited from serial audiometry, performed at intervals of 9–12 months. Many combinations of grouping by sound level, exposure duration, and frequency for TTS and for the slope of deterioration were employed. These comparisons, at the initial assessment, served to indicate further lines of enquiry which were subsequently followed and will now be described.

Full investigation

This was pursued in two distinct ways. The first method used data consisting of (a) hearing level relative to the British Standard audiometric zero, and (b) TTS together with the age and exposure history of the subject. The second approach compared TTS with the rate of deterioration of hearing derived from the serial audiometry measurements (Appendix 12). These methods will be described in the above order.

Comparison of TTS with presumed noise-induced hearing loss

The starting point is the value of TTS (at a particular frequency or mean of a number of frequencies) which the subject has acquired after exposure to a particular noise for a working day. The comparison of TTS with H depends upon the derivation of estimates of TTS and of H, not in absolute values, but as deviations from their average value within a group of subjects classified by L_{A2} (see Appendix 2). Thus, the difference between a recorded TTS value and the mean value might be compared with the difference between an observed value of H, and the median value of H, predicted from the individual's noise exposure. This predicted value is derived by the use of Appendix 10. In this way subjects with widely differing noise exposure, in terms of noise level and duration, and in consequence, widely different TTS and H values could be gathered into larger groups or even into one large group, for the purpose of correlation.

Index D_T

An additional refinement was introduced, for the following reason. It has been noted (1) that TTS and hearing level each measured at the same frequency are inversely related in a noise exposed population. In consequence, for an exposure of 8 hours, or 1 working day, to the same occupational noise, for any given frequency, different TTS values will be obtained in different persons, depending on their hearing level at that frequency, irrespective of individual susceptibility to TTS. Also, for the same reason the same TTS could result from exposure to different sound levels. It thus appeared to be desirable to apply some normalising procedure to the recorded values of TTS to eliminate this effect. This could be done, to a first approximation, by determining the linear regression of TTS on hearing level for a particular frequency, and from the slope extrapolating the individual TTS values back to 0 dB hearing level re British Standard zero ($H'_0=0$). The individual values of TTS normalised in this way could then be expressed as deviations in dB from their mean.

In the full analysis by KDF9 computer the same result was achieved without actually expressing TTS corrected to 0 dB H'_0. Instead, the normalised deviations D_T are the values, positive or negative, of the displacement in dB of the recorded value of TTS (ordinate) with

respect to the regression line of TTS on H_0', at the appropriate value of H_0' (abscissa).

Subjects were classified according to sound level L_{A2} of their occupational noise. Three groups resulted, as described in Table 13.1.

TABLE 13.1

Groups of subjects classified by sound level L_{A2}

Group	Sound level L_{A2} (dB)	Number of subjects
A	99 – 104	53
B	94 – 98	82
C	88 – 93	83

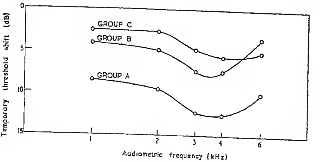
The actual mean values of temporary threshold shift, measured as described later under Procedure, for these three groups of subjects are given in Fig. 13.1 in an audiogram-like presentation. The derivation of D_T from the regression line of TTS on H_0' for the mean of 1 and 2 kHz is shown in Fig. 13.2, for group A.

Index D_P

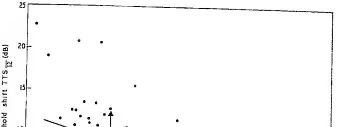
For correlation with the values of D_T, an equivalent index describing the degree of presumed noise-induced hearing loss was devised. This index (D_P), also in dB, positive or negative, describes the deviations of the observed age-corrected hearing level relative to controls or presumed noise-induced hearing loss (H_{obs}), measured in a particular person, from the median values of noise-induced hearing loss (H_{calc}) predicted from the particular noise exposure by the method described in Appendix 10.

$$D_P = H_{obs} - H_{calc}$$

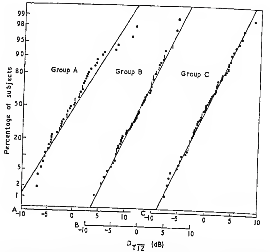
As a necessary preliminary to the comparison of D_T and D_P, these indices were examined to determine the nature of their statistical distributions. In the case of D_T, as shown in Fig. 13.3 for the average of 1 and 2 kHz from group A, the distribution is approximately Gaussian; D_P for 3, 4 and 6 kHz from group A (Fig. 13.4) also



13.1 Temporary threshold shift values for a nominal 8-hour (i.e. one work day) exposure to sound levels L_{A2} as follows: Group A, 99-104 dB; Group B, 94–98 dB; Group C, 88–93 dB. For time lapse between cessation of noise and TTS measurement, see text.



13.2 Derivation of D_T values. The deviations from the regression line of TTS on H'_o, positive or negative, constitute the values of D_T. Group A; L_{A2}, 99–104 dB. Average of 1 and 2 kHz on both axes.



13.3 Cumulative percentage distribution of values of D_T for the average of 1 and 2 kHz, for Groups A, B and C. The lines through the points indicate the Gaussian distribution corresponding to the standard deviation of the D_T values for each group.

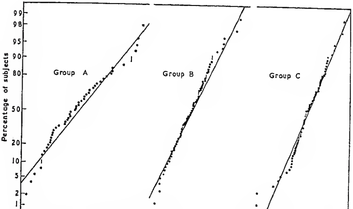
shows no great departure from normality. The other groups and frequencies show similar characteristics.

Procedure

Within the practical limitations of the field study conditions, measurements of TTS were made when conditions were suitable, on volunteer subjects who participated in the retrospective and serial measurements. In all, TTS was measured throughout the audiometric frequency range on 565 occasions. Initially, because of the fact that an interval of 2 min after the end of exposure yields the greatest values of TTS reliably obtainable, and due to the particular pattern of the recovery process with time (2), we attempted to get the audiometry started at this post-exposure interval. However, in the conditions found in the field, it soon became evident that 2 min was too short, and subsequently a post-exposure starting time of 6 min was adopted, which was the minimum time found to be necessary to reach the audiometric unit and settle the subject for the test.

In each case, data on the noise, duration of exposure in months, and the age-corrected hearing level at the various audiometric frequencies were necessary.

Of the TTS measurements available, some were repeated 2 or 3 times with the same person on different days. These cases were averaged, by taking the arithmetic mean of the decibel values of TTS. Similarly, the corresponding value of H was the arithmetic mean of the various decibel values recorded at the same time as the TTS estimations. The exposure duration was the mean of the durations, in months, at the different occasions on which H and TTS were measured. The standardisation on 6 min post-exposure audiograms for the TTS data, the reduction in number of individual values due to averaging the double or triple estimations in certain individuals, and a number of unavoidable exclusions of individuals for various reasons, reduced the definitive subject numbers to 218. The numbers of measurements of TTS are shown on Table 13.2, and the various steps necessary for the D_T/D_P correlation, with explanatory notes, are now summarised.



13.4 Cumulative percentage distribution of values of D_P, for the average of 3, 4 and 6 kHz for Groups A, B and C. The line indicates the equivalent Gaussian distribution for each group.

TABLE 13.2
TTS test numbers

Group	No. of subjects having			Total no. of subjects	Total no. of TTS tests
	1 test	2 tests	3 tests		
A	40	13	—	53	66
B	61	16	5	82	108
C	69	11	3	83	100
Totals	170	40	8	218	274

Step 1. DERIVATION OF DEVIATIONS (D_T) OF TTS FROM THE REGRESSION LINE OF TTS ON H'_O

The audiometric data consisted of hearing level re British Standard zero (H'_O), measured before starting work in the morning, and again at the conclusion of the day's work. The audiometers were programmed to record the post-exposure audiograms in the following order of frequency

3	4	6 kHz				left ear
0·5	1	2	3	4	6 kHz	right ear
0·5	1	2	3	4	6 kHz	left ear

The audiogram was in every case started as nearly as possible 6 min after leaving the noise, normally $\pm\frac{1}{4}$ min. At the rate of scanning the frequencies of 30 sec per frequency, the audiogram occupied 30×15 sec=7·5 min; consequently each frequency and frequency combination was measured at a particular post-exposure interval.

The recorded TTS values were obtained from the difference of the hearing levels immediately before, and normally beginning 6 min after the end of a normal working day (or shift):

$$TTS = H'_{O\ \text{post-exposure}} - H'_{O\ \text{pre-exposure}}$$

TTS was expressed as the arithmetic mean, in dB, of the individual TTS values in both ears for the following frequencies:

1 kHz
mean of 1 and 2 kHz
„ „ 2 and 3 kHz
„ „ 1, 2 and 3 kHz
„ „ 3, 4 and 6 kHz
„ „ 1, 2, 3, 4 and 6 kHz

Where a TTS average value was derived from one measurement in the right ear and two in the left, (i.e. where a combination included 3, 4 or 6 kHz), the average was arranged to retain equal weighting for the 2 ears.

For these various frequencies linear regressions of TTS were determined on recorded hearing level H_O' for the same frequencies. The deviations D_T were obtained for each subject, corresponding to the vertical displacement of the recorded TTS value from the regression line in dB, positive or negative.

Step 2. DERIVATION FROM AUDIOMETRIC DATA OF AGE-CORRECTED HEARING LEVEL RELATIVE TO CONTROLS (H_{obs})

The audiometric hearing level relative to British Standard zero (H_O') was corrected to be relative to the hearing level of controls not exposed to noise (H'):

For persons under 20 years of age

$$H_{obs}=H_O'-H_O'{}_{\text{controls}}$$

For persons over 20 years of age, it was assumed (Appendix 10) that the effects of age and of noise were substantially independent and the appropriate age correction, in decibels, was subtracted from the value of H_O' using a smoothed version of Hinchcliffe's (3) data:

$$H_{obs}=H_O'-C_i\,(N-20)^2-H_{O\ \text{controls}}$$

where C_i is a coefficient depending on frequency, and N is the age of the person in years. (See Table 10.3 of Appendix 10 for values of C).

Step 3. PREDICTION, FROM SUBJECT'S NOISE EXPOSURE, OF MEDIAN AGE-CORRECTED HEARING LEVEL RELATIVE TO CONTROLS (H_{calc})

(a) calculate the subject's noise immission level (NIL) as

$$E_{A2}=L_{A2}+10\log{(T/T_O)}$$

where L_{A2}=sound level A exceeded for 2% of the time

T =exposure duration on the basis of approximately 8 hours/day, 5 days/week. Unit: 1 month. Where 2 or more measurements of TTS were made on different occasions, T is the mean of the corresponding durations.

T_O =reference duration, 1 month.

(b) Use the formula from Appendix 10 to predict, from E_{A2}, the median value of H_{calc}.
Where a combination of frequencies is used, the value of H_{calc} employed is the average of the separate values for the individual frequencies.

Step 4. CORRELATION OF D_T AND D_P

Calculate the linear regressions and correlation coefficients for D_T and D_P, as described under Results.

DERIVATION OF NON-NORMALISED TTS INDEX D_T'

For comparison with the index D_T, a modified index D_T' was also derived. This index is similar in concept to D_T, except that it is the deviation, in dB, of each TTS value from the arithmetic mean of all the values for each frequency or frequency combination in the Group A, B or C, without the normalising adjustment described in Step 1.

Results

CORRELATION OF TTS AND H_O'

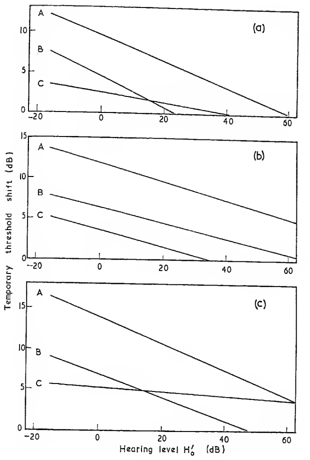
Illustrations of the regressions of TTS on H_O' for three of the frequency combinations are shown in Fig. 13.5 for groups A, B and C. On Table 13.3 are given the complete data for the regressions of TTS on H_O'.

CORRELATION OF D_T AND OF D_T' WITH D_P

Using the method outlined above, and on the basis of various preliminary trials, regressions of D_T on D_P were determined for the following frequency combinations (Table 13.4) for groups A, B and C. The bar symbol here and subsequently denotes an average value.

In Table 13.5 are given the details of the regressions of D_T on D_P, and of D_T' on D_P, for the various frequency combinations, in groups A, B and C.

Three-dimensional plots of the values of the product-moment correlation coefficient for each frequency combination are shown in Fig. 13.6 (for D_T/D_P) and Fig. 13.7 (for D_T'/D_P).



13.5 Regressions of TTS on H_0' for the frequency averages: (a) 1 and 2 kHz, (b) 2 and 3 kHz, (c) 3, 4 and 6 kHz, for Groups A, B and C. TTS and H_0' are for the same frequency combination in each regression.

TABLE 13.3

Regression of TTS on Hô
(TTS and Hô measured at same frequency)

Frequency kHz	Slope	Correlation coefficient r	Significance level P
GROUP A			
1	−0·144	−0·217	0·12
$\overline{12}$	−0·159	−0·267	0·055
$\overline{123}$	−0·105	−0·232	0·10
$\overline{23}$	−0·113	−0·281	0·05
$\overline{234}$	−0·139	−0·347	0·012
$\overline{346}$	−0·168	−0·397	0·004
$\overline{12346}$	−0·148	−0·344	0·012
GROUP B			
1	−0·252	−0·359	0·001
$\overline{12}$	−0·190	−0·291	0·01
$\overline{123}$	−0·127	−0·226	0·05
$\overline{23}$	−0·096	−0·169	0·14
$\overline{234}$	−0·116	−0·210	0·06
$\overline{346}$	−0·144	−0·256	0·02
$\overline{12346}$	−0·137	−0·248	0·025
GROUP C			
1	−0·098	−0·165	0·20
$\overline{12}$	−0·063	−0·104	0·40
$\overline{123}$	−0·050	−0·079	0·50
$\overline{23}$	−0·104	−0·139	0·25
$\overline{234}$	−0·080	−0·107	0·75
$\overline{346}$	−0·028	−0·036	0·70
$\overline{12346}$	−0·031	−0·046	0·35

TABLE 13.4
Frequencies used for regression of D_T on D_P (kHz)

D_T	D_P
1	$\overline{46}$
1	$\overline{346}$
$\overline{12}$	$\overline{12}$
$\overline{12}$	$\overline{234}$
$\overline{12}$	$\overline{346}$
$\overline{12}$	$\overline{46}$
$\overline{12}$	$\overline{12346}$
$\overline{23}$	$\overline{234}$
$\overline{23}$	$\overline{346}$
$\overline{123}$	$\overline{234}$
$\overline{123}$	$\overline{346}$
$\overline{346}$	$\overline{12}$
$\overline{346}$	$\overline{346}$
$\overline{12346}$	$\overline{12346}$

Discussion

REGRESSION OF TTS ON H'_0

Referring to Fig. 13.3 it is clear that D_T at $\overline{12}$ kHz, for groups A, B and C, for practical purposes, can be regarded as a normally distributed variable. The configuration of the audiogram-like curves of Fig. 13.1 resembles permanent noise-induced change in the dip in the region of 4000 Hz. The finding that, in a noise-exposed population, TTS is inversely related to hearing level is substantiated wholly by all the regressions of TTS on H'_0 in Table 13.3. In Fig. 13.5, the regression slopes are shown graphically for 3 frequency combinations. The higher the exposure sound level, the greater is the TTS value and there is a broad tendency for the higher frequencies to show greater slopes. This trend is, however, by no means general, and numbers of discontinuities in the picture can be observed. The slopes of the regressions of TTS on H'_0 in the various groups tend also, but with many exceptions, to become less as the sound level of the exposure is reduced, with a corresponding reduction in the significance of the correlation coefficients which are nevertheless invariably negative. As will be seen below, the frequency which forms the best basis for D_T for the regression of D_T on D_P is the mean of 1 and 2 kHz. The correlation coefficient r of D_T on H'_0, in this case, just fails to reach the 0·05

Table

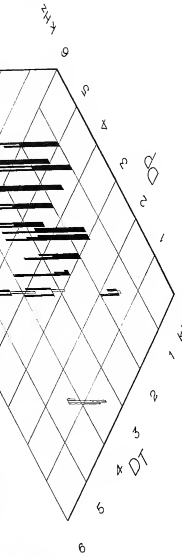
Correlation

Frequencies used in regressions kHz D_T	D_P	Normalisation of TTS (Yes or No)	Group A: Correlation coefficient r	Significance level P	Slope: D_T on D_P	D_P on D_T
Column 1		2	3	4	5	6
1	$\overline{46}$	Yes	0·229	0·10	0·087	0·603
		No	0·155	0·30	0·060	0·397
1	$\overline{346}$	Yes	0·279	0·05	0·111	0·698
		No	0·198	0·20	0·081	0·485
$\overline{12}$	$\overline{12}$	Yes	0·072	0·70	0·048	0·109
		No	−0·165	0·30	−0·114	−0·238
$\overline{12}$	$\overline{234}$	Yes	0·288	0·05	0·122	0·677
		No	0·113	0·50	0·050	0·258
$\overline{12}$	$\overline{346}$	Yes	0·340	0·02	0·129	0·900
		No	0·207	0·20	0·081	0·527
$\overline{12}$	$\overline{46}$	Yes	0·297	0·05	0·107	0·826
		No	0·182	0·20	0·068	0·488
$\overline{12}$	$\overline{12346}$	Yes	0·289	0·05	0·143	0·584
		No	0·114	0·50	0·058	0·221
$\overline{23}$	$\overline{234}$	Yes	0·197	0·20	0·082	0·473
		No	−0·027	0·90	−0·012	−0·063
$\overline{23}$	$\overline{346}$	Yes	0·290	0·05	0·108	0·780
		No	0·099	0·50	0·038	0·255
$\overline{123}$	$\overline{234}$	Yes	0·215	0·20	0·083	0·556
		No	0·037	0·80	0·015	0·094
$\overline{123}$	$\overline{346}$	Yes	0·299	0·05	0·103	0·869
		No	0·149	0·30	0·053	0·421
$\overline{346}$	$\overline{12}$	Yes	−0·105	0·50	−0·080	−0·138
		No	−0·329	0·03	−0·273	−0·396
$\overline{346}$	$\overline{346}$	Yes	0·064	0·70	0·028	0·148
		No	−0·257	0·10	−0·121	−0·545
$\overline{12346}$	$\overline{12346}$	Yes	0·101	0·50	0·047	0·218
		No	−0·178	0·30	−0·088	−0·360

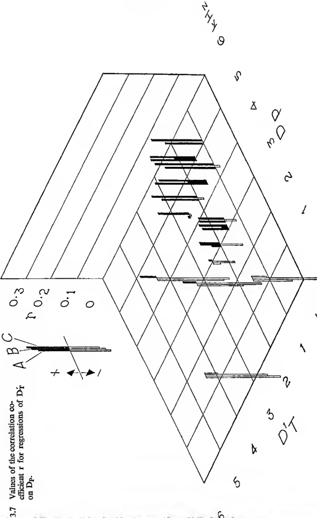
13.5

f D_T and D_P

Group B				Group C			
Correlation coefficient r	Significance level P	Slope D_T on D_P	Slope D_P on D_T	Correlation coefficient r	Significance level P	Slope D_T on D_P	Slope D_P on D_T
7	8	9	10	11	12	13	14
0·143	0·20	0·082	0·250	0·276	0·02	0·141	0·539
−0·005	0·70	−0·003	−0·008	0·213	0·10	0·110	0·410
0·142	0·30	0·082	0·248	0·289	0·01	0·168	0·499
−0·021	0·85	−0·013	−0·034	0·225	0·05	0·132	0·382
−0·003	0·98	−0·002	−0·004	0·041	0·80	0·025	0·068
−0·272	0·02	−0·190	−0·389	−0·056	0·70	−0·034	−0·092
0·221	0·05	0·112	0·435	0·174	0·20	0·103	0·292
0·032	0·80	0·017	0·061	0·108	0·40	0·064	0·180
0·226	0·05	0·105	0·490	0·228	0·05	0·124	0·418
0·079	0·50	0·038	0·162	0·181	0·10	0·099	0·331
0·217	0·05	0·101	0·468	0·221	0·05	0·106	0·460
0·092	0·50	0·045	0·191	0·179	0·15	0·086	0·370
0·172	0·20	0·102	0·292	0·174	0·15	0·109	0·278
−0·036	0·80	−0·022	−0·058	0·102	0·40	0·064	0·162
0·048	0·70	0·029	0·078	0·120	0·30	0·081	0·178
−0·092	0·50	−0·057	−0·148	0·012	0·95	0·008	0·017
0·108	0·40	0·060	0·195	0·192	0·10	0·120	0·309
−0·010	0·95	−0·006	−0·018	0·116	0·30	0·073	0·185
0·096	0·40	0·050	0·187	0·138	0·30	0·077	0·249
−0·086	0·50	−0·046	−0·163	0·081	0·50	0·045	0·145
0·141	0·30	0·066	0·299	0·222	0·05	0·114	0·430
−0·017	0·90	−0·008	−0·034	0·180	0·15	0·093	0·348
−0·130	0·30	−0·121	−0·140	−0·030	0·80	−0·023	−0·039
−0·238	0·05	−0·229	−0·247	−0·050	0·70	−0·039	−0·065
−0·088	0·50	−0·056	−0·136	0·080	0·50	0·056	0·114
−0·294	0·01	−0·196	−0·441	0·055	0·70	0·039	0·078
−0·054	0·70	−0·034	−0·086	0·087	0·50	0·056	0·140
−0·257	0·02	−0·167	−0·397	0·053	0·70	0·034	0·084



13.6 Values of the correlation coefficient r for regressions of D_T on D_P.
The position of the bars (one each for Group A, B and C) on the horizontal surface indicates the frequency or average of the frequency combination used for deriving the indices that are correlated. The height of the solid bars indicates, on the vertical scale, the positive value of r. Negative values of r are shown, on the same scale, as open bars pointing down below the horizontal surface.



3.7 Values of the correlation coefficient r for regressions of D'_T on D_P.

level (actually $P=0{\cdot}055$ approximately) for group A and is significant at the level $P=0{\cdot}01$ for group B. In group C, the regression slopes tend to have low values, as would be expected (Fig. 13.5) and r does not attain significance for any frequency in this group. In general, in groups A and B, r retains significant or very significant levels, but not so in group C. We did not feel, in view of the much smaller effect of the normalisation procedure in deriving D_T in Group C, that its exclusion was necessary, and so for the sake of conformity it is included with the other groups.

REGRESSION OF D_T ON D_P

The index D_P has already been explained and at this stage it is sufficient to note that its distribution (Fig. 13·4) is approximately Gaussian, for groups A, B and C for the frequency combination $\overline{346}$ kHz.

The full details of the various regressions of D_T on D_P are shown in Table 13.5, in the lines marked "yes" in column 2. The trend of the results is more readily appreciated by reference to Fig. 13.6.

The tendency is clear. The regressions of D_T on D_P where D_T is derived from the lower frequencies and D_P from the higher frequencies yield the higher values of the correlation coefficient r, and for these frequency combinations all r values are positive. That is to say for these frequency combinations, susceptibility to TTS may be expected to be associated with susceptibility to permanent noise-induced threshold shift in the same individual. The effectiveness of any test which attempts to predict the possible future extent of occupational hearing loss must depend on the accuracy of the estimate, as it concerns a given individual. Inspection of Fig. 13.6 and Table 13.5 shows that the highest value of r is $+0{\cdot}340$, and that the regression giving the highest value of r, averaged over groups A, B and C, is derived from the same frequency combinations, viz. the average of 1 and 2 kHz for D_T and the averages of 3, 4 and 6 kHz for D_P. For this regression in groups A, B and C the significance of r is $P=0{\cdot}02$, $0{\cdot}05$ and $0{\cdot}05$ respectively. Clearly any attempts to formulate a predictive test should be based on this frequency combination. Before considering this aspect further, however, it is necessary to enquire critically into the basis of the D_T/D_P correlation, in order to examine the circumstances of the underlying assumptions, in case any factor has been introduced artificially which could, in itself, contribute to significant positive correlations of D_T and D_P.

Critical examination of the correlation of D_T and D_P

The concept of D_T and D_P is based on the desirability of having some numerical indices of relative susceptibility to TTS and to permanent noise-induced hearing loss which could be applied over a range of values of the associated variables, such as H_0' and sound level (L). It was found preferable to use decibel values of D_T and D_P rather than a dimensionless quantity such for example, as the ratio of the value in dB, of observed to calculated values of noise-induced hearing loss. Such indices are very sensitive to fluctuations in the values of the basic quantities, for example when the denominator of the fraction becomes small. This objection has been met simply by the use of differences in dB as in the case of D_T or D_P. Taking the case of the index D_P, it has the desirable quality of general applicability over the range of values of hearing level (H_0'), but its value is in fact quite strongly associated with the value of H_0'.

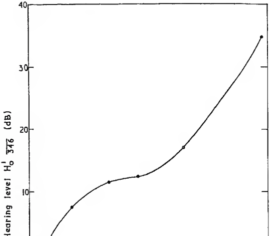
The latter is determined by a number of factors, including the intrinsic individual threshold value, variability in the audiometric performance, age, ear pathology, and noise-induced hearing loss. In the group with which we are concerned, pathology has been eliminated; age does not contribute greatly, due to the nature of the subject selection, but noise-induced hearing loss (H) is important. If H_0' is plotted against D_P for the average of 3, 4 and 6 kHz it can be seen in Fig. 13.8, where each point represents the average value for a group of approximately 9 subjects, that there is a general tendency to a positive correlation.

With regard to D_T, this index can be seen also to be associated with H_0' because by definition D_T is the deviation from the regression line of TTS on H_0'. Since this regression is negative, a measured value of TTS will yield a value of D_T which is directly related to the value of H_0' of the subject in the sense that high values of H_0' generate high values of D_T, and vice versa (Fig. 13.2).

We must therefore conclude that the value of H_0' is capable of influencing both D_T and D_P, and in the same direction, so that a positive regression of D_T on D_P might be generated artificially, in the process of normalising TTS deviations to take account of different values of H_0'.

In order to assess the implications of this conclusion a number of lines of enquiry are open to us. In the first place, let us consider the situation of D_T with regard to H_0'. In Fig. 13.2, the regression of TTS

on H_0' for the average of 1 and 2 kHz has a slope of $-0{\cdot}159$, with a correlation coefficient of $r=-0{\cdot}267$, and significance just under $P=0{\cdot}05$. These regression slopes tend to increase in steepness with increase of sound level and also to vary systematically with audiometric frequency. However, the less the slope of the regression of TTS on H_0', the less would be the influence on D_T by the normalising procedure. With lower noise levels D_T would be less influenced by H_0'. On the other hand, lower values of TTS would also result thus allowing the various sources of variability to operate to greater



13.8 Relation of D_P to H_0' for the average of 3, 4 and 6 kHz for Group A. Points represent averages of approximately 9 subjects.

effect. The influence of H_O' on D_T would be non-existent if all subjects had the same value of H_O' before exposure to noise. This condition could in theory be approximately attained within arbitrary limits of H_O', by choice of subjects, but to secure these, and other necessary conditions in a field situation would be a near impossibility.

Elimination of the effect on D_T would be attained if normalisation were omitted altogether, the deviations (D_T') of the TTS values being expressed relative to their mean, (as described above), instead of to the regression line of TTS on H_O'.

The result of this is seen in Fig. 13.7 and in Table 13.5 where, for each frequency combination, the correlation for D_T' and D_P is designated "without normalisation" in column 2. The correlation coefficients for these cases are appreciably lower and in general they do not match the significance levels attained for D_T/D_P, although in one case in group C, the regression of D_T' at 1 kHz on D_P at 3, 4 and 6 kHz averaged, r is in fact significant at P=0·05. However for the frequency combination yielding the highest values of r for D_T/D_P correlations, the trend still operates and positive correlations for D_T'/D_P are found.

In view of the total independence of the measures D_T' and D_P, it is reasonable to conclude that the occurrence of positive correlations between D_T and D_P is a real effect, and not adventitiously produced. Although normalisation does produce higher correlation coefficients, it can be regarded as a legitimate device to oppose the effect of the negative regression of TTS on H_O'. Even after normalisation, some isolated negative correlations of D_T on D_P remain. Their origin is not clear, but they only occur for high frequency/low frequency D_T/D_P regressions.

Study of Table 13.5 and Fig. 13.6 leaves the impression that, at best, the correlation of D_T and D_P is at a fairly low value, despite the satisfactorily high (up to P=0·02) significance attained by the highest values of r. The maximum values of r are of course limited by the variability introduced at the different stages, and it is to be expected that the higher the noise level, and so the greater the TTS, the less will be the effect of the various sources of variability.

In view of the somewhat small values of r (+0·340) for the most favourable circumstances (correlation of $D_{T\overline{12}}$ with $D_{P\overline{346}}$ for group A) it is of interest to enquire how these arise from the viewpoint of the known or estimated components of variability. First, it is obvious that if means of groups of subjects, instead of individuals were used

for this correlation, the values of r would increase markedly. For example for groups of subjects numbering approximately 9 per group, the value for r for the above correlation increased from +0·340 to +0·744. This however, is not helpful, since it is the performance of individuals which concerns us. However, as is done in Appendix 12, if one assumes the correlation of D_T and D_P to be direct and fundamentally perfect, potentially yielding r=+1·0, it is possible to determine the theoretical maximum value of r which would be obtained, in the presence of the estimated components of variability, by the use of the following expression.

$$r=\left\{\frac{\sigma_x^2-\sigma_\delta^2}{\sigma_x^2}\cdot\frac{\sigma_y^2-\sigma_\epsilon^2}{\sigma_y^2}\right\}^{\frac{1}{2}}$$

where σ_x^2, σ_y^2 are the total observed variances of $D_{T\overline{12}}$ and $D_{P\overline{346}}$ respectively and σ_δ^2, σ_ϵ^2 are respectively their random variances (i.e. not attributable to the correlation).

Assigning the appropriate variances to these quantities results in the following

$$\sigma_x^2=20{\cdot}3\ \mathrm{dB}^2$$
$$\sigma_y^2=142{\cdot}4\ \mathrm{dB}^2$$

These are the experimentally derived quantities for group A.

Turning to the random variance components, in the case of D_T, normalisation has not affected this variance, which we estimate from the replication variance of TTS obtained from the 13 subjects for whom we have 2 or 3 separate measurements of TTS. The value is 16·2 dB². Two determinations of TTS having been involved, we infer that the variance becomes

$$\sigma_\delta^2=8{\cdot}1\ \mathrm{dB}^2$$

Finally, in the case of $D_{P\overline{346}}$ the random term σ_ϵ^2 implies the component of the total variance σ_y^2 which cannot be expected to be associated with the variation of D_T. Thus it must contain the inter-subject variance (σ_S^2 of Appendix 10 Table 6) exhibited by subjects not exposed to noise, of 17 dB², together with the error or intra-subject variance σ_O^2 appropriate to the L_{A2} value of the group.

From Appendix 10 Table 6, we infer a value for σ_O^2 of 53 dB². This value, however, refers to a 2-ear average for one audiometric frequency. In our case three frequencies (3, 4 and 6 kHz) have been

averaged so that the variance becomes 53/3=18 dB^2 approximately. The total value of random variance for $D_{P\overline{346}}$ kHz now becomes.

$$\sigma_\epsilon^2=35 \text{ dB}^2$$

Applying these values to the above expression we find that the value of r cannot be expected to exceed +0·67. Thus the best value obtained for the D_T/D_P regressions (+0·34) is not as discouraging as it might appear.

One other observation remains, in the context of the correlations with D_T with D_P. Since the D_P component is derived from hearing level measurements and, as we have seen, is strongly influenced by H, some of the variability of D_p can be removed by deriving it from the difference between the hearing level at $\overline{12}$ kHz and $\overline{346}$ kHz. Only the size of the dip in the audiogram now operates and fluctuations in the level of the whole audiogram are eliminated. Using this device for the regression of $D_{T\overline{12}}$ on $D_{P\overline{346}}$ for group A, the value of r is raised from +0·34 to +0·38. We are left, after these explorations, with the inescapable conclusion that the operation of the variables present in normal pure-tone air-conduction audiometry sets a limit to the correlation obtainable from the various indices of TTS and of H, and consequently to the possibility of asserting that the two kinds of susceptibility are invariably associated in individual cases.

Comparison of TTS with indices derived from serial audiometry

The second method of study of the possible relations of TTS to occupational hearing loss is by a direct comparison between TTS or some derivative, and the rate of deterioration in a noise-exposed individual.

By utilising the data in Appendix 12, which derives from serial audiometry, such comparison is possible. This has been done and the results of the correlation of D_T on various measures of progression of hearing impairment are given in Table 12.8 of Appendix 12. The somewhat disappointing result, which is the best we can report, is that the rank order of the index Y/X (Appendix 12) with D_T yields a correlation coefficient of 0·28, with a significance of P=0·10. The trend is nevertheless present and once again, we must incriminate the large component of variability, from numerous sources, in reducing the probable significance of these correlations.

Prospects for a test of susceptibility to noise-induced hearing loss

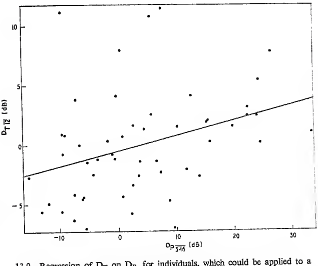
In the light of these findings various theoretical possibilities may be suggested for a test of susceptibility to permanent noise-induced changes. We shall examine how far existing information can point the way to a practical test.

Such tests, in the light of the correlation between TTS and H, as measured by the indices D_T and D_P, could clearly take the form of tests for susceptibility to TTS. Ideally, if a measurement of TTS as a result one day's work could give enough information to predict how much loss an individual would sustain after a given number of years in the same noise, great benefits would accrue. The critical aspect concerns the extent to which, for a simple test of this nature, quantitative relations can be pushed so as to establish with sufficient accuracy the probability of a certain individual sustaining a certain degree of occupational hearing loss after a stated occupational noise exposure.

In devising such tests, there is an overwhelming advantage in using a normal day's work in the particular occupational noise as the stimulus for producing TTS. Such a course is clearly much more convenient than the administration of a specially devised acoustic stimulus, but certain limitations exist. In the first place, the best basis for the index D_T has been shown to be the average TTS for the 1 and 2 kHz audiometric frequencies and thus this frequency combination is clearly the best basis for the test. At the environmental sound levels which we would not wish to exceed for daily exposure over a long period of years, viz about 90 dB(A), the numerical value of TTS at these frequencies would probably be, on average, about 10 dB measured 2 min after the end of the day's exposure. The 2 min post-exposure value is not always easy to achieve in industry, but this difficulty could be overcome by the artifice of prolonging the noise exposure until the subject is ready for audiometry by means of a portable tape recorder and earphones. In the data at our disposal here, somewhat lower values of TTS are found, due to the longer interval between cessation of the noise and measurement of TTS. This is not a fundamental factor, and taking the data we possess, a possible test could be envisaged along the following lines.

For illustration we employ group A, the mean noise level of which is nearly 101 dB L_{A2}. Taking a permissible median value of H at

4 kHz at the fairly generous level of 20 dB, (as has been advocated by some (4) for an exposure duration of 10 years or more) by the use of the procedures described in Appendix 10, we find that an exposure duration of approximately 13 years would result in this median value of H. The corresponding value of H for the mean of 3, 4 and 6 kHz is 17 dB; these values refer to a mean prediction for a population approximately equally divided between men and women. We assume that it is desired to identify some specified proportion of those most susceptible to noise-induced hearing loss, and for the example we select the 5th centile level. Referring to Fig. 17 in Appendix 10 we find by interpolation that this gives a value for H of about 28 dB above the median value. Thus the D_P value is by definition also 28 dB. We now wish to find the corresponding value of D_T in group A, and accordingly we refer to Fig. 13.9, and enter the abscissa at 28 dB. Reading horizontally from the regression line to the ordinate,



13.9 Regression of D_T on D_P, for individuals, which could be applied to a predictive test. D_T: average of 1 and 2 kHz. D_P: average of 3, 4 and 6 kHz. Group A, sound level L_{A8} 99–104 dB.

we find the value on the D_T scale, viz 3·0 dB. To translate this into an actual value of TTS, as measured, we refer to the regression of TTS on H'_O for the audiometric frequency average at 1 and 2 kHz (Fig. 13.2). If the individual had a resting hearing level of 0 dB, measured as the average of his hearing level at 1 and 2 kHz, relative to the British Standard ($H'_{O\overline{12}}$), his total TTS would be expected to be the mean value for this exposure, viz 9·5 dB, plus 3·0 dB=12·5 dB. Where an individual's resting hearing level $H'_{O\overline{12}}$ departs from 0 dB the measured TTS $_{\overline{12}}$ is normalised to 0 dB H'_O as already described. Thus such individuals, showing 12·5 dB or more of normalised TTS, could be regarded as potentially at risk.

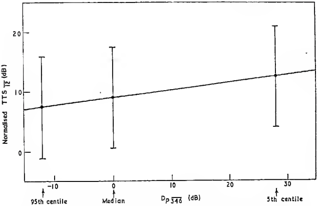
This, however, is not the complete picture, since a tolerance must be applied to the normalised TTS value. This is provided by the value of the residual variance of D_T in the D_T/D_P regression of Fig. 13.9. This variance is nearly 18 dB^2, corresponding to limits, for P=0·05, of ±8·5 dB. Thus for those with $H'_{O\overline{12}}$ values of 0 dB, the limit value of 12·5 dB now becomes a limits range of 12·5± 8·5 dB (Fig. 13.10). This figure also shows the situation for the 95th centile (noise-resistant) group, and for the median. The overlap of the ranges is a crippling disadvantage, so that this type of test in its present form cannot give all the needful information. For example, in Fig. 13.10 only the TTS values over 17·5 dB can be said with confidence to have originated in the more susceptible half of the population. Even then, they only constitute a fraction of that half.

If the example quoted above is applied to a more acceptable sound level, specifically not more than 90 dB (A) or just under 94 dB L_{A2}, the situation becomes even less favourable. If our underlying hypothesis that there is a fundamental relation between D_T and D_P is pressed to the limit it would be permissible to derive D_T from a chosen value of D_P by means of the geometric mean regression slopes between the two indices, rather than by the more conservative use of the slope of D_T on D_P. By this means, the overlap of the tolerances on the measured values of D_T illustrated in Fig. 13.10 would be somewhat diminished.

This type of test is obviously not yet a fully effective procedure for routine purposes. Further effort must be directed to increasing the value of the coefficient of the correlation of D_T and D_P. It will be recalled that, where average values of D_T and D_P within groups of persons numbering about 9 per group, instead of individuals, were used, the correlation coefficient rose to +0·744, about the same value

as resulted from a removal of the known or estimable variances. There are various directions in which further refinement should be possible.

The most obvious is to ascertain the effect on the correlation of D_T and D_P of greater numbers of observations from the same person. Thus, if the whole process of morning and evening measurements of hearing level were performed on 4 consecutive days, higher correlation coefficients would undoubtedly result. This, while not impossible in practice, would be tedious. The small proportion of results derived from such multiple estimations in the present data is not likely to have elevated the coefficients to any appreciable extent above the value resulting from one test only. The index D_P, as we have noted, is influenced by hearing level. The extent to which this effect occurs is least at high values of noise-induced hearing loss, and maximal if no noise exposure has occurred; at zero noise exposure, D_P would consist entirely of the value of the departure of the hearing level from zero hearing level relative to the standard used. We have not detected any appreciable influence of this circumstance in our



13.10 Values of normalised TTS for average of 1 and 2 kHz, Group A, indicating different centile levels of probable permanent noise-induced hearing loss, expressed as the average of the loss at 3, 4 and 6 kHz, as a result of the same noise as produced the TTS. The bars cover a range of ±2 standard deviations.

data, since no subjects are included with zero known noise exposure, and those with short durations of exposure, due to the rapidity of the growth of H in the early stages (Appendix 10, Fig. 1) still had noise induced losses which were not negligible. In this connection also, D_P may be derived in a modified way. This merely involves the substitution of the value $(H_{\overline{346}} - H_{\overline{12}})$ for $H_{\overline{346}}$ in calculating D_P (Appendix 12). Thus it is the size of the 4 kHz dip which is used in deriving D_P rather than the absolute value of H at $\overline{346}$ kHz. The effect of individual differences in the pre-exposure hearing level may then be expected to be largely eliminated. This modification is of sufficient value to be employed routinely. In the normalising procedure, we are satisfied that, over ranges of exposure in our data, the inverse relation of TTS and H_O' can be used with confidence. It would however, be of interest to investigate further the effect of hearing level on TTS for those without known noise exposure. Our data do not indicate any obvious discontinuities in TTS as H_O' is diminished. Thus decrease of hearing level appears to be associated with increase of TTS down to values of hearing level at and below 0 dB H_O'. Various means are open to us, within the confines of conventional pure-tone audiometry, to reduce variability. For example, instead of complete repetition of the TTS measurements, over perhaps 4 days, modified audiometric techniques could be devised to concentrate on the relevant frequencies, and to diminish the post-exposure delay before measurement. It is conceivable that a different stimulus might be necessary, but these aspects must await later investigation.

At the present time, therefore, while the situation seems to us to be considerably clarified on the relations between temporary and permanent effects, a routine practical test is not yet within our grasp.

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Appendix 14

Noise-induced hearing loss in pathological cases

by W. Burns, Barbara E. Wood, J. C. Stead and H. W. Penney

The reasons for the inclusion of a number of categories of subjects broadly designated 'pathological' have been given in Chapter 4 (see page 25). This Appendix deals with the pattern of noise-induced hearing loss exhibited by these categories, which for convenience will be labelled pathological. They are compared, in terms of hearing changes, with the subjects in the definitive retrospective study, whose hearing was unimpaired except for the effects of occupational noise.

The categories in this Appendix were derived as described in Appendix 8. While the various categories are in the main in the realm of aural pathology, one category includes those with a history of head injury and another of exposure to gunfire. The complete categorisation of subjects by conditions or histories was as follows:

Category P1 conductive hearing loss
P2 vertigo
P3 sensorineural hearing loss (other than noise-induced, traumatic or associated with vertigo)
P4 history of exposure to gunfire noise (other than air-gun or ·22 rifle)
P5 history of head injury, with definite history of unconsciousness and/or subject's statement that radiological evidence of skull fracture had been obtained.

Because these cases appeared on our books in the early stages fortuitously, and in the later stages by intention, they do not constitute in any way a guide to the relative incidence of such conditions in industry. Indeed, as the terms of reference indicate, the whole design of the investigation was directed to the acquisition of a population free from aural pathology, except for the effects of occupational noise.

Of the total number of subjects excluded from the main study, not all were suitable for the pathological category, due to uncertainty in

the noise history, or the impossibility of quantifying their noise environment. This left the individuals with which we are concerned in this Appendix (Table 14.1). The categories P2 and P3 are so small in numbers that little information could be extracted from them; P2 will not be considered further. This leaves 213 cases of gunfire exposure, head injury, conductive hearing loss and sensorineural hearing loss in that order numerically, which we can compare with the subjects in the retrospective part of the study.

TABLE 14.1
Summary of pathological cases

Category	Type of aural pathology	Number of subjects
P1	Conductive hearing loss	35
P2	Vertigo	2
P3	Sensorineural hearing loss	10
P4	Gunfire	114
P5	Head injury	54
	Total	215

Experimental procedure

The approach used was dictated somewhat by the numbers of subjects available. Ideally, large numbers in each of the various pathological categories would be compared audiometrically with control groups matched for age and exposure. Clearly, we could hardly expect to obtain such conditions. Fortunately, in the course of the investigation an index has been developed which in the present context suits our purpose. This is the index D_P (Appendix 13). It is a measure in dB of the difference between an individual's observed hearing level and the median value of hearing level to be expected on the basis of his age and noise exposure. It is found thet D_P is distributed, in non-pathological ears, in an approximately normal manner (Appendix 13). The occurrence of hearing impairment due to aural pathology or factors other than noise may be expected to produce a tendency towards higher values of D_P, and perhaps to alter their distribution. We can thus examine the hearing of the noise-exposed pathological groups against the background of the usual pattern of noise-induced impairment in otherwise normal ears.

Methods

The basic data used in this Appendix consisted of the following: serial number of subject; age; sound level L_{A2}; exposure duration, diagnosis of aural condition, and which ear affected; audiogram on one or more occasions.

From the above data the following were derived.

MEAN HEARING LEVELS

The audiometric data were extracted to give average hearing levels relative to the British Standard (H'_O) for right (R) and left (L) ears separately, expressed as arithmetic means in dB of the values at 0·5, 1 and 2 kHz ($H_{R\cdot\overline{512}}, H_{L\cdot\overline{512}}$) and at 3, 4 and 6 kHz ($H_{R\ \overline{346}}$, $H_{L\ \overline{346}}$).

Notes:

(a) Where more than one set of audiograms was available, data from the same ears were averaged.

(b) Where for any reason, a person's category was changed from normal to pathological, only data for the latter condition were used.

(c) Where more than one audiogram was obtained, the age-correction of H'_O was that for the mean of the ages at which audiometry was performed.

(d) In the circumstances of (c) the exposure duration for calculation of D_P (Appendix 13) was the mean of the exposure durations at the times of the audiometric examinations.

CALCULATIONS OF D_P FOR PATHOLOGICAL EARS

From the above information the value of D_P was calculated exactly as described in Appendix 13. In categories P1 and P3 where the pathology might reside in the right or left ear or both, the D_P values were calculated for right and left ears combined, and separately for pathological and non-pathological ears. In categories P4 and P5, where the effects of head injury or gunfire would not be expected to show major differences in the two sides, the data are given for right and left ears, and for both sides combined. In all cases the low and high frequency D_P values were calculated separately, since individual consideration of these frequencies is of interest in all the categories. Means and medians of the individual values in each category were derived as summarised below. Except for medians for R and L ears combined in categories P1 and P3, all combined values are for the average of 2 ears.

CATEGORIES P1 AND P3

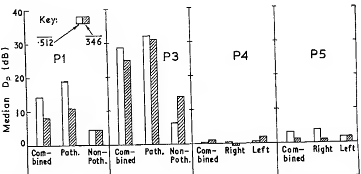
D_P values for $\overline{\cdot 512}$ R and L averaged
„ „ „ $\overline{\cdot 512}$ pathological ears (R, L or both)
„ „ „ $\overline{\cdot 512}$ non-pathological ears (R or L)
„ „ „ $\overline{346}$ R and L averaged
„ „ „ $\overline{346}$ pathological ears (R, L or both)
„ „ „ $\overline{346}$ non-pathological ears (R or L)

CATEGORIES P4 AND P5

D_P values for $\overline{\cdot 512}$ R and L averaged
„ „ „ $\overline{\cdot 512}$ R
„ „ „ $\overline{\cdot 512}$ L
„ „ „ $\overline{346}$ R and L averaged
„ „ „ $\overline{346}$ R
„ „ „ $\overline{346}$ L

Results

These derivatives of the D_P values for categories P1, P3, P4, P5 are shown in Table 14.2 and Fig. 14.1. Table 14.3 shows, in addition, basic data on age and noise exposure for these categories.



14.1 Illustration of the differences between observed age-corrected hearing levels and values of presumed noise-induced hearing loss calculated on the basis of noise exposure, in groups having other conditions associated with hearing impairment. These differences are expressed as D_P values for averages of low (1 and 2 kHz) or high (3, 4 and 6 kHz) frequencies, for groups P1, P3, P4 and P5.

TABLE 14.2

Median and Mean Values of D_P

Frequency and ear kHz R or L	Category											
	P1			P3			P4			P5		
	Median	Mean	Number of ears	Median	Mean	Number of ears	Median	Mean	Number of ears	Median	Mean	Number of ears
$\overline{\cdot 512}$ R & L combined	14·3	16·5 (133·0)	70	28·7	27·8 (211·4)	20	0·4	0·3 (54·8)	228	3·3	4·2 (26·2)	108
$\overline{\cdot 512}$ Pathological ears	18·9	21·5 (223·6)	50	32·1	34·3 (378·8)	14						
$\overline{\cdot 512}$ Non-pathological ears	4·5	4·5 (40·9)	20	6·3	12·4 (126·6)	6						
$\overline{346}$ R & L combined	8·1	10·6 (110·6)	70	24·7	26·7 (199·4)	20	1·0	3·2 (156·6)	228	1·1	3·1 (51·5)	108
$\overline{346}$ Pathological ears	10·3	14·0 (196·1)	50	31·2	32·5 (474·5)	14						
$\overline{346}$ Non-pathological ears	4·6	2·0 (90·8)	20	14·1	13·2 (201·6)	6						
$\overline{\cdot 512}$ R							0·1	−0·1 (67·8)	114	4·1	4·1 (29·0)	54
$\overline{\cdot 512}$ L							0·5	0·71 (52·8)	114	1·8	4·3 (32·4)	54
$\overline{346}$ R							−0·6	2·1 (172·1)	114	1·1	2·5 (68·7)	54
$\overline{346}$ L							2·0	4·4 (171·5)	114	1·8	3·7 (59·6)	54

Values in brackets are variances in dB^2

TABLE 14.3

Category	P1	P3	P4	P5
Mean age (years)	24·8	28·7	31·2	22·2
Mean L_{A_8}	92·2	95·1	99·1	93·9
Equivalent L_A	88·5	91·4	95·4	90·2
Mean exposure (years)	5·9	8·8	9·7	4·4
NIL	96·2	100·9	105·3	96·6

Discussion

It must be emphasised that these data do not in any way possess the qualities of an incidence study, and their function is to provide an indication of how audiometric information can be handled when the usual picture of noise-induced hearing loss is complicated by other factors. We are not in a position to give any meaningful picture of the progress of noise-induced change in the presence of different kinds of aural pathology, since this was not in our terms of reference.

Study of Table 14.2 and Fig. 14.1 reveals some interesting aspects. We recall that the use of the index D_P eliminates the need for a specific matched control population, since this is in effect provided by our population of noise-exposed subjects, the basic information being readily available by inspection of the nomogram of Fig. 10.17, or the equivalent equation, of Appendix 10.

Inspection of Fig. 14.1 immediately shows that the median D_P values are positive with one trivial exception, and that marked elevation (i.e. positive values) of the D_P medians occurs in categories P1 and P3, but not in P4 and P5. Before more detailed consideration it must be remembered that category P1 numbers 35 subjects and P3 only 10. Thus no general conclusions are possible in these categories, but some comment is permissible.

In the case of P1 in the pathological ears, and to a lesser extent (as would be expected) in the combined R and L ears, the median $D_{P\cdot\overline{12}}$ exceeds the value of the median $D_{P\overline{346}}$. This is generally in accord with clinical expectations. The non-pathological ears show similar values for the lower and higher frequency combinations. While there is no requirement that the median D_P should be zero, due to sampling effects, there is a suggestion that some degree of deterioration may have existed in a number of the 20 ears graded clinically

"normal". Another aspect of the use of D_P in cases of conductive hearing loss is of interest. If the loss were purely conductive, the effect would be equivalent to wearing ear defenders permanently. In the long run, this would result, in theory, in a degree of deterioration due to noise which would be less, and would progress more slowly, than in the case of an unprotected normal ear. In the application of D_P there would thus be a tendency to reduction of its value due to the fact that the assumed value of H_{calc} (Appendix 10) was erroneously high. However, D_P would be elevated by the pathological deafness, and the outcome of the operation of these two factors would vary according to their relative magnitudes at a given time. The data are hardly adequate for further exploration of this aspect.

In category P3, which only contains 10 persons, their expected median hearing levels are clearly greatly exceeded, actually by some 30 dB in the ears diagnosed as pathological. What is perhaps less typical is the rather similar value of D_P for the $\overline{\cdot 512}$ and $\overline{346}$ kHz cases. These subjects have in fact large losses at the lower frequencies and the very small number of subjects must be implicated in these findings. The non-pathological ears also showed appreciable positive values of D_P, more marked at the higher frequencies in this case. It might be argued, particularly for the $\overline{346}$ kHz case, that high values of pathological loss, in presence of high noise exposure (NIL) would produce a saturation effect, but at least for the median values, these conditions do not appear to have been reached. However, on the basis of this small and miscellaneous sample, it is not possible to speculate further. From the clinical viewpoint, it is of interest to compare the mean D_P values of category P3 for pathological ears (Table 13.2), with their corresponding audiometric values, which are: $\overline{\cdot 512}$ kHz, 34·5 dB H_0'; $\overline{346}$ kHz, 43·0 dB H_0'.

Categories P4 and P5, consisting of persons excluded from our basic data because of a history of exposure to gunfire (P4) or of unconsciousness due to head injury (P5) both present only small departures (D_P) from the expected median values of hearing loss, especially so in the case of subjects exposed to gunfire. The finding of Hinchcliffe that in gunfire deafness from small arms fire the left ear usually tends to suffer more (presumably associated with a normal right-handed handling of the gun) is of interest. The left ears at the 3, 4 and 6 kHz audiometric frequencies do show a slightly greater excess hearing level than do the right. The difference however is not statistically significant ($P = 0{\cdot}20$).

In the case of category P5, the D_P values, (accepting small anomalous variations from the main results of the investigation attributable to sampling vagaries) are small. Appreciable high-tone losses can be found in head injury, but in our sample this effect is not seen, and in fact what changes there are affect the lower frequencies preferentially.

The values of the variances of P1 and P3 show a considerable range, the very high values in P3 being indicative of the miscellaneous nature of the few individuals in this category. In category P1 the difference between the pathological and non-pathological ears is obvious. By far the smallest variances are found in P5. Category P4, while showing somewhat larger variances, has only trivial median departures from the definitive experimental population of noise-exposed subjects.

We consider in the light of the data, that D_P is a useful index in the documentation of hearing levels of persons with both noise-induced hearing loss and loss suspected of being due to some other cause. It may be of diagnostic use where the noise exposure of the person is known. Compared to our non-pathological noise-exposed population the departures of the medians of categories P4 and P5 are so small that the inclusion of these categories as non-pathological subjects would probably have had no marked effect. It must be remembered however, that the rigour of our criteria for admission to the definitive population was such that many of the P4 cases had very slight exposure to gunfire. Nevertheless it would be highly inadvisable to extend this conclusion further, for it is well known that gunfire exposure, or even a single bang from a firework, may be potent sources of noise-induced hearing loss. Likewise, 4 kHz dips can originate from cranial injuries. On this evidence, in attempting to assess the effect of noise on hearing for purposes of compensation in subjects with these various conditions, the conclusions we draw are as follows.

In the categories of conductive and sensorineural loss, separate consideration of individuals with significant noise exposure is necessary. In the case of gunfire, the minimum levels of exposure we encountered apparently produced negligible effects. However, the known serious effects of this type of noise should not be overlooked. It thus seems desirable to attempt to differentiate between levels of gunfire exposure in order to clarify its probable effects. In the case of head injury, again on the basis of our small sample there seems little justification for drawing any distinction between these conditions and that of persons without such a history. The small variances we have

found in category P5 lend weight to this conclusion, which implies that the mean and median values are not concealing large individual hearing losses.

Appendix 15
Relation to other work on PTS and TTS

by D. W. Robinson and W. Burns

Permanent noise-induced threshold shift

There are numerous published reports of retrospective studies dealing with workers in particular industries or subject to noises with special features such as gun-blast. The majority of these are of the incidence kind so that, as pointed out elsewhere in this report, it is not to be expected that the results would compare at all closely with ours. Of the remainder we know of only half a dozen studies in which investigators pursued aims similar to ours, that is, to determine the specific effects of noise on ears little or not at all impaired by other causes, and in circumstances of regular daily exposure for lengthy periods to noises of the kinds found in industry. Even amongst these, there are difficulties of comparison for various reasons.

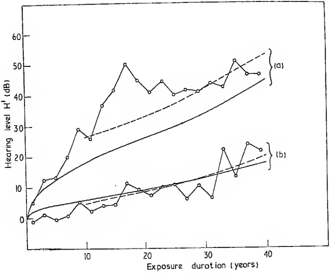
The major obstacle to systematic comparisons of the results of the different studies is that none except ours are presented in a generalised form, permitting interpolation of noise levels, durations or centiles of the populations to the conditions in each report. This means that each set of original, and usually unsmoothed, data has to be considered separately. A further difficulty is that there have been divergences, the effect of which is by no means easy to interpret, between the criteria for subject selection, and the extent to which exclusions have been made on the basis of otological examination. On this we can only infer that no investigation appears to have prescribed conditions more rigorous than ours, and in some cases clearly less so. For instance Gallo and Glorig (1) included persons with up to two years of military service, including the firing of weapons. In addition to these considerations some of the reports are obscure on material details, appear to be internally inconsistent or contain information at variance with generally accepted experience. For example, Nixon and Glorig (2), and also reference (1), show hearing levels for non-exposed control groups of around 0 dB ASA (3) whereas the ISO threshold level (4) which is based on a very extensive series of international exchanges relating to persons of normal hearing is some 10 dB below the ASA zero. There is also a

difference of a fairly fundamental kind between our findings and those of Gallo and Glorig which relates to the independence or otherwise of noise-induced and presbycutic loss. These authors found that the result of subtracting from the hearing levels of noise-exposed persons the value for control subjects of the same age group was a curve of presumed noise-induced threshold shift against exposure duration which reaches a maximum and then falls. Since it is contrary to reason that there should be a recovery from an already sustained loss while the cause persists, Gallo and Glorig conclude that the two effects are not additive in terms of threshold shifts in decibels. We have not found this, in fact the contrary forms an integral part of our proposed procedure for estimating the presumed noise-induced component of a person's hearing level. A possible explanation of Gallo and Glorig's finding may, however, derive from the argument in Appendix 10 Section 6.

A critical examination of all the available data would be a major undertaking beyond the scope of this report. No such appraisal has appeared in the literature, but recently an attempt at collating the work of eight investigations (1, 2, 5, 6, 7, 8, 9, 10) has been made by Mrs. Passchier (11) in the Netherlands. This highlights some of the discrepancies and culminates in a set of greatly simplified charts and formulae which sum up the whole of the information. We do not find ourselves wholly sympathetic to her particular treatment due to some artificial features which it introduces, such as linear relationships with a sudden break at 10 years and a sudden break at a particular noise level, where smooth curves are more likely to accord with reality. We should concede that it is impossible to be dogmatic about the exact nature of relationships in the face of experimental discord and that there is therefore much to be said for drastic simplification for practical purposes. The rules given by Mrs. Passchier are not, in fact, quite as simple as ours, there being two sets of empirical curves and tables of parameters depending on the frequency. Her method, however, provides a most useful framework for a comparison of our work against a synthesis of the eight other studies. We shall go a little further than this and illustrate the relation between our findings and those of three out of the other eight authors, giving also Mrs. Passchier's values.

We have selected for this purpose the studies by Gallo and Glorig (1), by Taylor, Pearson, Mair and Burns (6), and by Kylin (8). The first-mentioned present the median, quartile and decile hearing levels

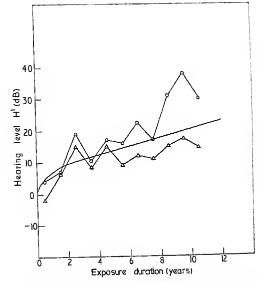
of 400 men exposed to noises averaging 97 dB(A) for periods of 0 to 40 years in bands of 2 years at 0·5, 1, 2, 3, 4 and 6 kHz, and of 90 women and a matched selection of 133 of the men for the same mean noise level in bands of 1 year up to 11 years for 4 kHz only. To facilitate comparisons with the male group we have averaged the median results at 0·5, 1 and 2 kHz and at 3, 4 and 6 kHz respectively, as shown in Fig. 15.1. The discrepancy between ASA and ISO reference levels would, if interpreted literally, add about 10 dB to all the plotted data of Gallo and Glorig, but the fact that their curves converge to a point near zero hearing level on their own scale for zero noise exposure leads us to believe that it is not correct to apply such an adjustment. On the other hand this necessarily implies, in its



15.1 Comparison of the hearing levels (not corrected for age) from Gallo and Glorig with the corresponding values from this investigation, and as predicted by Passchier's method. (a) Average of 3, 4 and 6 kHz; (b) of 0·5, 1 and 2 kHz. Symbols: Gallo and Glorig, o; this investigation, continuous line; Passchier's method, interrupted line.

turn, either a considerable calibration error or highly improbable sampling differences, or a combination of these with perhaps some additional discrepancy due to the manner of conducting the audiometry. The plotted results of Gallo and Glorig are not corrected for age; to effect a proper comparison our results are accordingly given in terms of H′ (see Appendix 10) and Mrs. Passchier's in the form specified in her report which adds a presbycusis correction (incidentally not the same as ours) to the presumed noise-induced component. The zero of the abscissa corresponds on average to 18 years of age. The agreement is reasonable for the lower frequencies, which we may refer to loosely as speech frequencies, but we show a smaller threshold shift at the higher frequencies

Gallo and Glorig found a considerable difference between men and women, which is illustrated in Fig. 15.2. To avoid complicating the



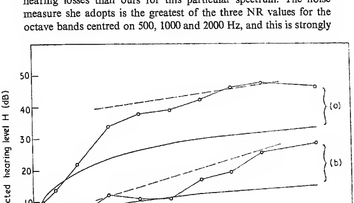
15.2 Comparison of Gallo and Glorig's results for men and women with results of this investigation. Frequency 4 kHz. Symbols: Gallo and Glorig, 133 men, o; Gallo and Glorig, 90 women, Δ; this investigation, continuous line.

diagram we show only the median results again. As in Fig. 15.1, the curves derived from this investigation are those for our total group of 759 subjects, of whom 422 were male and 337 female. These results, as can be seen, are intermediate between the other authors' male and female values, but the difference that they found between the sexes is greater than we did (see Appendix 10, section 5).

The high frequency discrepancy in Fig. 15.1 caused us to note a doubtful point of interpretation in the paper by Gallo and Glorig, which is in the direction of considerably reducing the divergence from our result. They give an octave band spectrum from which one may calculate an overall sound pressure level of 97·8 dB and an A-weighted sound level of 97·2, the latter being the value we used for the comparison. The authors, however, also measured the overall sound pressure levels of the noises directly, quoting the average as 102 dB. For nearly flat spectra such as the authors' average spectrum, there is little difference between the overall and the A-weighted sound pressure levels. It may therefore be more correct to have taken a value nearer 102 than 97, and in this case our prediction curve would be lifted to a position almost coincident with the broken line. The uncertainty is probably the result of an averaging process whereby Gallo and Glorig summarise a wide variety of noises by a single set of figures. There is an unavoidable element of arbitrariness in so doing, since there is no logical basis for preferring the mean of decibel values to that of the corresponding linear physical quantities. Mrs. Passchier's method is also based, though in a different way, on the octave band spectrum so that if ours were raised so should her curve be.

We consider next the work of Taylor, Pearson, Mair and Burns (5) on female workers in the jute industry. The noise level, calculated from their octave band spectrum, is 101·1 dB overall or 100·9 dB(A). These authors remarked on transients with peak amplitudes up to 18 dB above the mean level quoted, occurring up to 18 times per second. In view of our finding that hearing loss is related more closely to the measure L_{A2} than to the mean prevailing level L_{A50}, the former giving weight to peaks in the noise, it is possible that the comparison should be made with a level higher than 100·9 inserted into our formulae. From the information given, based on oscillographic observation, it appears on the other hand that the duration of these transients must have been too brief to have inflated the measure L_{A2} for the reasons described in Appendix 9. Accordingly we have accepted the unmodified value.

The data of Taylor *et al* are presented in the form of presumed noise-induced threshold shifts, and for the subtraction of the age effect they used the same presbycusis information as we. In this case, therefore, the present results are displayed in the form of H, and in computing by Mrs. Passchier's procedure the presbycusis correction is not added at the last step. The results are compared in Fig. 15.3, which again has been simplified by showing only the medians for the two combinations of low and high frequencies. Since the experimental data in this case refer exclusively to females we should have expected them to lie below our predictions for the mixed group, but the reverse is the case. Mrs. Passchier's method predicts considerably greater hearing losses than ours for this particular spectrum. The noise measure she adopts is the greatest of the three NR values for the octave bands centred on 500, 1000 and 2000 Hz, and this is strongly



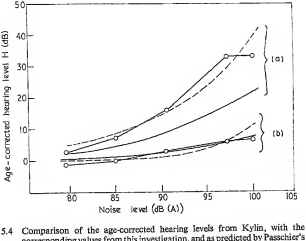
15.3 Comparison of the age-corrected hearing levels from Taylor, Pearson, Mair and Burns, with the corresponding values from this investigation, and as predicted by Passchier's method. (a) Average of 3, 4 and 6 kHz; (b) of 0·5, 1 and 2 kHz. Symbols: Taylor *et al*, o; this investigation, continuous line; Passchier's method, interrupted line.

influenced by the high point in Taylor *et al's* spectrum which happens to occur at 2000 Hz. The criteria of subject selection and otological examination used in this study, due to the common authorship of one of us, were very similar to those adopted in the present study, and for that reason the differing results cannot readily be explained.

Kylin (8) studied the hearing of 89 men classified in five bands of noise level and all having exposure durations between 10 and 15 years with a mean of 12; he also studied 29 male controls. The average age within each group including the controls was nearly the same (34 to 37) so that relative adjustments for presbycusis are not necessary in this case. Although the great majority of the men had had military service and an appreciable number reported non-military shooting, various ear diseases, head injury or other items which would have eliminated them from our study, it appears that the incidence of these factors was spread evenly over all the groups. With the exception of one further consideration, namely that 15 out of the 89 men admitted to having worked previously in noise louder than that of their current occupations, it seems not unreasonable to compare Kylin's results with ours provided this is done on the basis of hearing loss relative to controls. With the same simplifications as before the data are shown in Fig. 15.4. The abscissa is the noise level in dB(A) calculated from Kylin's octave band spectra for the different groups. Agreement is again good at the speech frequencies, but as before our results indicate smaller presumed noise-induced hearing losses at the high frequencies. Kylin also reports a small-scale study in which 20 noise-exposed women are compared with 17 of the men, so selected as to match the women one-to-one for age and noise level. These results are expressed as net losses compared with controls, the latter being the 29 male controls already mentioned and a separate group of female controls. The net loss for the men greatly exceeds that for the women; at 3, 4 and 6 kHz averaged, the values are 15·5 and 6·5 dB respectively. This difference is even larger than that found by Gallo and Glorig, and it is still more remarkable if one notes that the 15·5 dB average for the 17 selected males is well below the corresponding value read from the curve based on the larger male group of 89. The 17 men had a mean current exposure of 11 years (compared with 12 for the big group); 8 of them reported louder previous occupational noise; and the mean noise level was 95·0 dB(A) calculated from the octave band spectrum given. Reference to Fig. 15·4 shows that under these conditions the principal study yielded an interpolated value for

net hearing loss of about 27 dB. Our result for the mixed group is 14·2 dB. Fig. 15.4 includes the values calculated by Mrs. Passchier's method; the required values of NR were computed from Kylin's octave band spectrum and the presumed noise-induced hearing loss calculated therefrom. Since the results are compared relative to controls of corresponding age, no presbycusis correction was made. In order to show Mrs. Passchier's results on the same diagram the results of these calculations are plotted against dB(A).

To sum up, our high frequency results for a mixed population of men and women exceed the values given by Gallo and Glorig and by Kylin but fall short of those of Taylor *et al*, for women. They fall considerably short of the values for males summarised from eight other investigations by Mrs. Passchier. The difference we have found between male and female ears is in the right direction but insufficiently large to explain the discrepancy, but part of this may be ascribed to differences in subject selection criteria and a further part possibly by an alternative interpretation of Gallo and Glorig's average noise level. At speech frequencies there is general agreement between most of the



15.4 Comparison of the age-corrected hearing levels from Kylin, with the corresponding values from this investigation, and as predicted by Passchier's method. (a) Average of 3, 4 and 6 kHz; (b) of 0·5, 1 and 2 kHz. Symbols: Kylin, 89 men o; this investigation, continuous line; Passchier's method, interrupted line.

studies including ours; Taylor, Pearson, Mair and Burns, however, observed larger hearing losses. It may be possible to construe the divergences between the investigations in several ways. We have here made no attempt to argue the differences in terms of the statistical distribution of hearing levels within the populations but it is evident that even with comparatively large numbers of subjects, running into hundreds, there is likely to be disagreement about mean or median values, given that the variance for a noise-exposed group may be upwards of 200 dB^2 (see Appendix 10). Perhaps the source of the discrepancies may lie in quite a different direction, however. We have remarked, in discussing the data of Gallo and Glorig, that a difference in the assumed noise level makes a drastic change to the estimated hearing loss, about 2 dB in the latter for each dB in noise level. Throughout this investigation we have regarded the measurement of noise and the measurement of hearing level as being equally important; both are subject to uncertainty which we have tried to minimise by the procedures set out in Appendices 4 and 9 and the chapter in our main report entitled Audiometry. There appears to have been rather less attention paid to the noise measurement aspect in some other investigations, and this may be a contributory cause though not perhaps a very likely one for the rather one-sided divergences between our finding and others. On balance we incline to the view that the explanation resides mainly in the exclusion criteria; in support of this it seems to us fundamentally correct, in studies specifically intended to relate noise to hearing loss, that a lower bound must exist and that any deviations from it which are necessarily in an upward direction are evidence of other unidentified causes at work.

Temporary threshold shift

The desire for an indication of the degree of susceptibility to permanent noise-induced hearing loss has sustained interest in temporary threshold shift phenomena for many years. The fact that no effective and definitive test yet exists arouses no surprise in those who have sought to evolve one, nor does the profusion of proposed tests. The situation, up to the present, has been that much information has been obtained, especially by Ward (12) on the basis of laboratory experiments with temporary threshold shift (TTS); also, numbers of investigations devoted to occupational hearing loss have

been conducted, of which the most relevant to this study are cited in the first part of this Appendix. These two aspects have not been brought together to any great extent, so that there is a scarcity of information on the relations of temporary threshold shift to permanent threshold shift (PTS), despite the numerous tests of susceptibility to TTS which have been proposed.

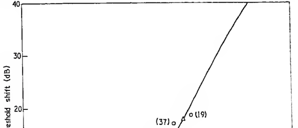
The best known mutual attribute of TTS and PTS is probably the relation between the TTS produced by a day's exposure and the presumed noise-induced hearing loss H, resulting from about 10 years of occupational exposure to the same noise (2, 7, 8, 13, 14). Specifically, the TTS accruing from an exposure of about 8 hours, measured 2 min after the end of exposure (15), (when the recovery is at the most reliable phase for measurement of maximum TTS) in young persons with unimpaired hearing, is approximately equal in decibels to the value of H after about 10 years of work in the same noise. Distinctions are drawn between the effects at different frequencies (16) but they are not large. Approximate numerical equality is attributed at 1 kHz, while at 2 kHz the TTS is regarded as being about 5 dB more, and at 4 kHz, about 3 dB less, than the noise-induced PTS at the corresponding frequencies. The duration in this estimate by Kryter, Ward, Miller and Eldredge (16), given as "many years of habitual exposure", is equated to about 10 years, and by implication applies to a condition when deterioration has for practical purposes ceased. There is difficulty in transferring this concept to the results of our studies, for we do not find that the process of deterioration due to noise has ceased after 10 years of exposure even at the 4 kHz frequency, where the most rapid deterioration occurs.

However, taking the value of TTS to be equivalent to that of H resulting from 10 years of exposure, we can examine how far our data correspond. For reasons explained in Appendix 13, it proved to be impractical, using our standard procedure, to record TTS at 2 min post-exposure. However, it is possible to calculate this value from the complex of post-exposure durations yielded by our audiometric procedure. For the illustration, we use the 4 kHz audiometric frequency. For this case, thresholds were determined in the left ear, right ear and left ear again, at mean post-exposure durations of 6·75, 9·75 and 12·75 min. Since Ward's data (12) show that recovery from TTS on average proceeds in a linear manner in dB as a function of the logarithm of time, it is possible to extrapolate back on such a

scale to the 2 min time. This procedure was carried out, and the resulting TTS_{2min} value for Group A, Appendix 13, was 18·1 dB. For the 53 subjects in this group, the mean value of H calculated on the basis of the mean sound level of the group of 100·9 dB L_{A_2}, for a duration of 10 years, was 18·2 dB. In viewing the extremely close (and to some extent fortuitous) agreement between TTS and H in this case, it should be recalled that the subjects did not correspond to the original conditions of the subjects of Glorig, Ward and Nixon (13) inasmuch as they had already sustained some, if modest amounts, of exposure. It might be that their hearing levels (mean value at 4 kHz= 15·0 dB) corresponded more nearly than the values would indicate, to those of the "young, normal ears" on which the original proposition (13, 16) was based, due to the disparity between the ASA audiometric zero used, and the BS zero in the case of our data. The mean hearing level of our group would thus change from 15·0 BS to 8·9 dB ASA. In this connection, the American data are stated to apply to persons with hearing levels not exceeding 15 dB ASA at any frequency. The two conditions of the subjects' hearing are thus not greatly dissimilar. In addition, on the expectation of Ref. 13, the TTS_{2min} at 4 kHz would be expected to be some 3 dB less than the 10 year H value. However so many variables in terms of audiometric zero, presbycusis correction, degree of clinical otological normality, and previous noise exposure are involved in any TTS-PTS relation, that close correspondence cannot be expected in the work of different laboratories, particularly in the derivation of the H component. This has already been shown in the first section of the Appendix. Nevertheless, the agreement between TTS_{2min} and $H_{10\,years}$ is in general substantiated, and another presentation is given in Fig. 15.5, on which the above illustration is also inserted. Here, on the basis of a different grouping of subjects derived from an earlier stage of the investigation (there being a partial overlap of the subjects of group A and the upper two of the other groups shown in the figure) the TTS, as a function of sound level, is compared with the 10 year calculated values of H. The correspondence is fairly good.

The variety of proposed tests for susceptibility to TTS has been illustrated by Ward (17), who tabulates 19 publications by various authors, describing tests involving temporary threshold shift. The assumption throughout is that TTS will somehow indicate potential vulnerability to PTS due to noise. The sound stimulus used to evoke TTS has been very varied. The shortest duration of the stimulus was

1 min and the longest 30 min. Pure tones were the most common type of sound and the frequency ranged from 250 Hz to 4000 Hz; some investigators used noise. Test frequencies ranged from 250 Hz to 6000 Hz. Ward (17) conducted an extensive enquiry into the relative properties of different types of stimulus and their resulting TTS, with the object of investigating the nature of susceptibility to TTS. The result is a somewhat bewildering variety of interrelations, illustrating that there are numbers of 'specific susceptibilities' sampled by different types of stimuli, as well as a 'general susceptibility' sampled by tones or noise centred at about 2 kHz or below. Men showed more TTS in response to low frequencies than did women; the opposite obtained at high frequencies. As a result Ward was not optimistic on the question of the validity of TTS as an indicator of PTS, and expressed his opinion in 1965 in the following terms. "If 2 persons work side by side in a given noise environment for many years one may show a much greater loss than the other. All so-called susceptibility tests—tests designed to separate out such 'tender-eared' persons



15.5 Relation between TTS at 2 min post-exposure and the presumed noise-induced hearing loss after 10 years of exposure to the same noise. Frequency 4 kHz. Symbols: TTS of 53 subjects (Group A, Appendix 13), Δ; TTS of 81 subjects, divided into 3 groups as shown, o; median value of H at 10 years of exposure, from Fig. 10.17, continuous line.

before exposure—assumed an affirmative answer to this question. However, there simply is no evidence that this answer is correct. The most optimistic view I can muster, after completing the analysis of a series of 21 weeks of susceptibility tests (mostly TTS indices) on a group of 49 normal-hearing young adults, is that it may be possible that susceptibility to NIPTS (noise-induced permanent threshold shift) from a particular noise can be predicted from knowledge of susceptibility to TTS from that same noise".

In the present study we also elected to use the occupational noise for the production of TTS.

Dealing first with the finding of Ward that small differences in TTS susceptibility occur which are associated with the sex of the subjects, we examined our data in group A, Appendix 13. This group consisted of 32 males and 21 females, who had sustained mean noise levels L_{A2} of 100·1 and 102·1 dB respectively. We adjusted the mean values of TTS for these groups of men and women to correspond with the grand average L_{A2} value for group A, viz 100·9 dB, with the results shown in Table 15.1.

TABLE 15.1

Comparison of male and female TTS, adjusted to the same sound level

Subjects	Frequency combination (kHz)	TTS (dB)
32 male	$\overline{12}$	10·4
	$\overline{346}$	13·9
21 female	$\overline{12}$	8·3
	$\overline{346}$	10·8
M—F	$\overline{12}$	2·1
	$\overline{346}$	3·1
	Mean	2·6

The greater susceptibility to TTS of the male subjects agrees with the findings of Ward (18) and may be viewed against the greater mean values of H for males already discussed in Appendix 10, Section 5.

We do not find a different relationship with frequency in this group, for TTS in men and women, as described by Ward (18). However, this is a small sample, and the conditions are not rigorous; such interpretation as is possible indicates, not so much an intrinsic difference as a slight relative displacement towards greater apparent susceptibility of male ears to noise-induced effects. We would not at this juncture be prepared to incline towards either a biological or an environmental explanation, and this example only indicates, in a tentative manner, the opportunities for expansion of this type of investigation.

Examining the literature for investigations of specific relevance to our own, we only cite the work of Jerger and Carhart (19). This paper, which seems to have received less attention than it deserves, attempted to perform the same sort of comparison between temporary and permanent effects as in our present study. Their index of TTS was derived, not from the magnitude of the threshold shift, but from the duration to arbitrary levels, so that it was a recovery rate index having the dimensions of time. The stimulus was a pure tone of 3 kHz at a sound pressure level of 100 dB and with a duration of 1 min. Following this initial test, the subjects, young men with 'normal' hearing, worked in a noisy occupation for 4 months. At the end of this period there was an interval, without noisy work, lasting 8 weeks, after which the subjects' hearing was measured again, thus establishing the extent of 'permanent' threshold shift. It was found that greater PTS was associated with longer recovery durations after the TTS test. The correlation coefficients were, like our own, fairly low, but of high significance. The actual values of the correlation coefficients were in fact very close to our own, but the means adopted for the comparison were somewhat different. Jerger and Carhart's conclusions were, inevitably, in the same vein as ours. However, their study and our own suggest an underlying relationship, which, if it could be freed of the confusions of cumulative variabilities at different stages, might well yield a practical test. To this end we have taken the knowledge of the relations between temporary threshold shift to occupational hearing loss somewhat further, and numbers of developments of potential usefulness suggest themselves. For example, the TTS index could be expanded to use not only TTS magnitudes, but recovery times also, so that the area under the TTS curve relative to the mean area for a group might be investigated as an alternative to D_T, the present index. In the light of the other

studies, we are satisfied that our approach is basically sound, that it has narrowed down the possibilities by optimising frequency combinations, and that the retention of our practice of using the actual work noise as the stimulus, both on grounds of convenience and of scientific validity, is justified for further investigations.

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Appendix 16

A note on the hearing level of the non-exposed controls

by D. W. Robinson

It will be apparent to the reader of this report that in some places we have expressed hearing levels in terms of a standard reference zero, and in others relative to our own control subjects. As described in Appendix 4 we went to considerable lengths to ensure not only that the audiometric results should be expressible in terms of the British Standard (BS 2497:1954) but that they should be so expressible in the most direct way, namely by the use of the British reference earphone and artificial ear (4026A type earphone and BS 2042 artificial ear). Our principal findings, however, do not explicitly depend on this basis of calibration. Thus the predictions of presumed noise-induced hearing loss H in Appendix 10, and the analysis of TTS data in Appendix 13 in terms of the susceptibility index D_P, both derive from the base-line of our group of 97 young non-exposed persons. The reason for so doing is that the values of H expressed in this way converge smoothly to zero for low noise immission levels, as illustrated in Fig. 10.16.

If the conditions of test had been the same as those of the investigations underlying the Standard, and if the Standard correctly states the threshold of hearing for young non-exposed persons of normal hearing, there should be no difference whichever basis were used, unless for some reason our control group were non-typical. The actual British Standard hearing levels for the average of our controls were not in fact zero, but had the values given in Table 16.1. The standard deviations are the square roots of the variance values

TABLE 16.1

Hearing levels of group of 97 controls

Frequency (kHz)	0·5	1	2	3	4	6
H_0' (re BS 2497)	−1·3	−4·6	−5·7	−1·9	−2·6	0·0
re ISO R389)	(−0·8)	(−4·1)	(−5·7)	(−3·9)	(−4·1)	(−1·0)
σ_S (dB)	4·6	4·9	5·5	5·6	5·8	6·7
95% confidence limits on H_0' (dB)	±0·9	±1·0	±1·1	±1·1	±1·2	±1·4

shown in Table 10.6, and from these are derived the 95% confidence limit ranges given in the third row of Table 16.1. Since the mean hearing levels depart from zero by amounts which reach statistical significance it is important to examine the control group results further to determine whether the deviations are in the nature of sampling error, or are traceable to the definition of the audiometric zero specified in the British Standard or our realisation thereof.

The recent revision of the Standard (BS 2497 Pt. I:1968) brings it into coincidence with the ISO recommendation R389 by minor changes to the numerical values of the reference equivalent threshold sound pressure levels at the different frequencies. No change of the basis of calibration is entailed, so that the hearing levels for the control group can be expressed in terms of the ISO and new British standards by simple adjustment of the values. The results are shown in brackets in Table 16.1. It is apparent that this modification is not in itself the explanation of the non-zero values.

Another factor which may be relevant is discussed in a paper by Delany and Whittle (1), where it is shown by means of an extensive and systematic series of subjective comparisons that small discrepancies remain within the ISO Recommendation. The latter gives the threshold of hearing in five ostensibly equivalent forms based on various national usages. How the discrepancies are distributed amongst the different specifications, and consequently whether there is any error in the particular one concerned here, i.e. the one specifying the 4026A earphone and BS 2042 artificial ear, is impossible to determine from the comparative study cited. It is, however, suggestive of the existence of uncertainties of the order two or three decibels in the normal threshold of hearing as currently standardised, and inferences as to the magnitude and sign of these may be drawn from the manifestation of consistent tendencies noted by users of the data when applied to apparently normal groups of listeners.

A number of such observations is listed in Table 16.2. The first row relates to the highly trained and selected group of 25 subjects used by Delany and Whittle in the study mentioned above. 10 of these subjects were over 25 years of age. The second row shows the results for the 22 school-leavers at their first audiometric tests in the present investigation (group E of Appendix 12). Thirdly we show the values for 33 young laboratory workers, obtained in 1963, during the course of pilot trials for the present work. Since the questionnaire, otological examination, method of test and equipment were identical

with those adopted in the main investigation the results might have been amalgamated with the 97 non-exposed industrial controls, but this was not done due to the possibility of other extraneous factors causing differences in semi-laboratory conditions and in the field. Finally we include 16 normal hearing subjects tested by Knight in another pilot trial of this investigation which was primarily a study of the learning effect. The subjects were professional, administrative and domestic staff of the Charing Cross Hospital Medical School, none with any previous experience of audiometry. The audiometer used was one of those subsequently fitted to the mobile audiometric laboratory.

The broad similarity of the results of all the groups tested by self recording audiometry is illustrated in Fig. 16.1, which leads us to conclude that there is no systematic bias in the values of hearing level of the 97 controls, and that the persistent deviations from British Standard zero are to be explained on grounds other than sampling error.

The study by Delany and Whittle (1) was carried out by means of an exacting form of manual audiometry, whereas the remainder of the data were acquired by means of the self-recording audiometers. The difference of apparent hearing level occasioned by variations of

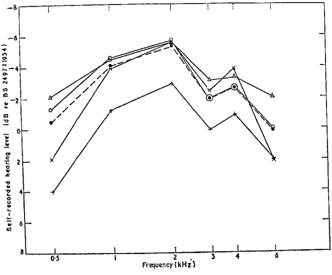
TABLE 16.2

Mean hearing levels of various control groups, expressed relative to British Standard zero

Control Group	Type* of audio-metry	Frequency (kHz) 0·5	1	2	3	4	6
25 trained subjects (Delany and Whittle 1967)	M	−3·2	−2·6	−1·6	+1·4	+0·2	+1·1
22 school-leavers (group E, Appendix 12)	S	+4·0	−1·2	−2·9	+0·1	−0·9	+2·1
33 young laboratory workers (Delany, 1963)	S	−2·1	−4·5	−5·6	−3·1	−3·3	−2·0
16 medical school staff (Knight, 1963)	S	+1·9	−3·9	−5·5	−2·4	−3·8	+2·1

*M—Manual
S—Self-recording

audiometric procedure or of equipment has been examined by several investigators but the most direct comparisons in the present context are afforded by two other pilot studies carried out respectively by Knight and Littler in 1963 in connection with the present investigation. In the first of these the hearing levels of 58 normal ears were compared using the ARJ-4 self-recording audiometer with 4026A earphones and an Amplivox Type 61 manual audiometer equipped with earphones having hard rubber earcaps. Both instruments were calibrated by the National Physical Laboratory to the British Standard of 1954. Littler's tests, carried out independently, used another Amplivox Type 61 modified with 4026A earphones, and one of the ARJ-4 self-recording audiometers. In this case the same earphones were used with both instruments, and they were not



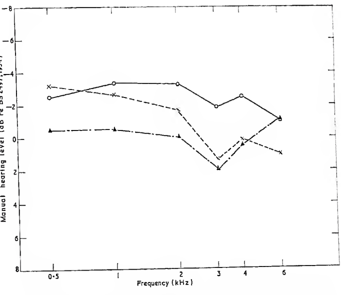
16.1 Hearing levels of various control groups tested by self-recording audiometry, expressed relative to BS 2497:1954. Symbols: 97 non-exposed industrial controls, o; 22 school leavers, +; 33 laboratory workers, Δ; 16 medical school staff, ×; weighted average, ●.

disturbed between tests. Littler tested 33 normal ears with this arrangement. Table 16.3 shows the weighted average result of these two investigations, as the difference of apparent hearing level using manual and self-recording audiometry, at various frequencies.

TABLE 16.3

Difference of apparent hearing level using self-recording and manual audiometry

Frequency (kHz)	0·5	1	2	3	4	6
Difference $H'_{OS}-H'_{OM}$	+2·0	−0·8	−2·1	−0·1	−0·2	+1·0



16.2 Grand average hearing level of controls corrected to "manual" technique compared to 25 controls tested by manual audiometry. Symbols: 168 controls, self-recorded audiometry corrected to equivalent manual values, o; 25 subjects, manual audiometry, (Delany and Whittle), ×; ISO Recommendation R389, ▲.

The subjects gave an apparently poorer hearing result at 0·5 kHz with the self-recording instrument. In Knight's study on the learning effect, referred to above, this defect disappeared in repeats of self-recording audiometry, but we are presently concerned with the retrospective investigation in which the first test by each subject is of concern.

The difference given in Table 16.3 has been applied to the weighted average of the hearing of all the control groups tested by self-recording audiometry, to obtain an estimate of the equivalent "manual" hearing level. The result is shown in Fig. 16.2, where it is compared with the directly-obtained manual hearing levels from the study by Delany and Whittle. The agreement is seen to be close, except for a progressive departure towards the higher frequencies, which is in the expected direction due to the age distribution in Delany and Whittle's subject groups.

Particularly noticeable is the shape of the curves on Fig. 16.2, on which is also shown the ISO threshold, relative to the former British Standard. Except for the last-mentioned at 6 kHz, the similarity is striking.

Bearing in mind the residual uncertainties in the ISO standard, underlined by Delany and Whittle, and the indirect inference of equivalent manual thresholds for the combined group of 168 controls in Fig. 16.2, the conclusions are as follows: the 97 industrial controls give results consistent with other controls; their average hearing level is about 3 dB better than ISO standard and similar at all frequencies except 6 kHz where there is some evidence that the former British Standard is more correct than the revised (i.e. ISO) value; finally that the difference of apparent hearing level obtained by manual and self-recording audiometry in the pilot studies is borne out indirectly by the results of the large control group.

Consideration of the aspects of familiarisation and learning leads us to suggest that, in view of the apparently greater ease of the subjects in deciding their auditory threshold at middle frequencies particularly 2 kHz, the routine order of presentation of frequencies in self-recording audiometry could well be revised. Moreover the abrupt and unannounced switch from one ear to the other seems to unsettle subjects, with apparent elevation of the threshold. The introduction of a dummy frequency might be advantageous. Thus the test might take the following form:

0·5 kHz	practice session,	left ear
1	dummy run	,, ,,
2	test	,, ,,
3	,,	,, ,,
4	,,	,, ,,
6	,,	,, ,,
6	,,	right ear
4	,,	,, ,,
3	,,	,, ,,
2	,,	,, ,,
1	,,	,, ,,
0·5	,,	,, ,,
0·5	,,	left ear
1	,,	,, ,,

Reference

1 Delany, M. E. and Whittle, L. S. *Acustica* 1967, **18**, 227.

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